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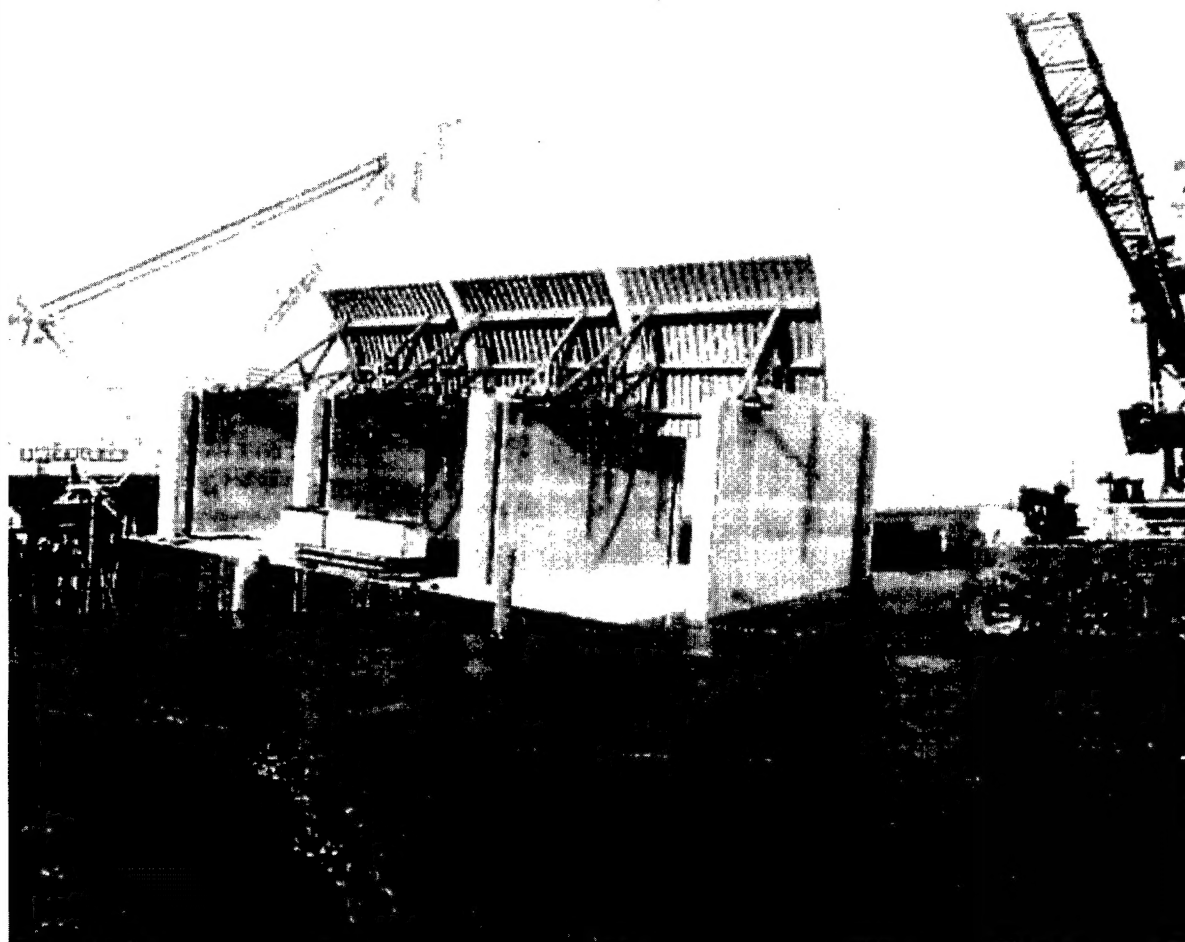
**US Army Corps  
of Engineers®**  
Engineer Research and  
Development Center

*Innovations for Navigation Projects Research Program*

## **Risk Assessment Procedures for Innovative Navigation Projects**

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December 2002



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# Preface

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The work described in this report was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Innovations for Navigation Projects (INP) Research Program. The study was conducted under INP Work Unit 33236, "Quantifying Risks and Uncertainties of Innovative Construction Techniques."

Dr. Tony C. Liu was the INP Coordinator at the Directorate of Research and Development, HQUSACE; Research Area Manager was Mr. Barry Holliday, HQUSACE; and Program Monitors were Mr. Bruce Riley, Mr. Mike Kidby, and Ms. Anjana Chudgar, HQUSACE. Mr. William H. McNally of the U.S. Army Engineer Research and Development Center (ERDC) Coastal and Hydraulics Laboratory was the Lead Technical Director for Navigation Systems. Dr. Stanley C. Woodson, ERDC Geotechnical and Structures Laboratory (GSL), was the INP Program Manager.

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At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and COL John W. Morris III, EN, was Commander and Executive Director.

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# 1.0 Introduction

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## 1.1 Background

This risk assessment study was conducted as part of ongoing research and computer programming efforts at the U.S. Army Engineer Research and Development Center, Vicksburg, MS, under sponsorship of the U.S. Army Corps of Engineers' Innovations for Navigation Projects Research Program.

Probabilistic techniques have developed in recent years into an effective means of assessing risk assumed during the design and construction of major projects similar to the innovative construction currently under way on the Braddock Dam project. Studies have indicated that the innovative construction methods being used for the construction of Braddock Dam are the most cost-effective means of construction and are within the current technical capabilities of the construction industry. Some uncertainties relative to the risk being assumed by these innovative construction concepts are anticipated. A risk assessment is a method to identify, estimate, quantify, and evaluate these risks.

## 1.2 Objective

The objective of this study is to demonstrate risk assessment methodology procedures for innovative inland waterways projects. The procedure is demonstrated by application to selected examples of each major procedural task. The use of an existing project, Braddock Dam, provides a definitive construction sequence from which to develop an extended project hazard identification list, discuss or show the usage of event trees for selected hazard items, and evaluate the consequences of selected hazard items in terms of cost.

The study is applicable to the selected time frame after construction bid award and just prior to start of construction of Braddock Dam. This time frame was selected in order to have sufficient construction event definition to assess the risks of events that are elements of an innovative construction program. However, these types of risk assessment studies can be undertaken at a variety of phases in the project life. These stages include feasibility, design and analysis, plans and specifications, and construction.

The Braddock Dam assessment study examples are based on currently available risk assessment data. If comprehensive risk assessment data for the construction events selected in this study are not available, recommendations will be made to obtain or develop the data. Furthermore, historical data for examples of similar marine construction are provided as one method of quantifying and thus providing an independent check for validating the risk assessment results.

## 2.0 Research Approach

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### 2.1 General Description of Methodology

The formal management of risks in a technological system such as the design, construction, and operation of dams involves both assessing and controlling the events that cause losses of property or other resources. A description of the methodology includes the definitions and concepts that are used in this study. The most appropriate methods and tools for addressing the current study objectives can be defined in terms of these definitions and concepts.

This study demonstrates the use of formalized methods to aid in the *control* of risks through the use of *risk assessment*, as shown in Figure 2-1. The word *risk* implies both the frequency (or probability) of adverse events and their consequences.<sup>1</sup> In this case the control of risks (such as the potential delay of the schedule or loss of property in the construction of the Braddock Dam) includes all aspects of decision-making that might affect the frequency or the consequences of the risk. Our primary focus here is on the supporting role of *risk assessment*, which includes both the analysis and the evaluation of the risk. The latter, *risk evaluation*, is the consideration of individual, corporate, and societal values and tolerances with respect to the costs and consequences. This may involve, for example, a simple comparison of fatal accident frequencies with those found tolerable historically in other fields or subtle economic analysis of the unavoidable trade-offs between costs and risks to the various stakeholders in the activity.

The still narrower, primary focus of this section, however, is *risk analysis* of technical systems, which is an engineering discipline that addresses the use of the information available to estimate the risk (both frequencies and consequences) of the hazards faced. A *hazard*, which is a major parameter in risk analysis, is nonetheless rather loosely defined in practice; it is any condition that may potentially cause an undesirable consequence. It may range from an initiating cause, such as a major storm during the tow, through an event somewhere in the course of one or more accident chains, such as a major structural failure, to some "end" state (for example, loss of buoyancy).

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<sup>1</sup>At a minimum, the risk of an event is the product of the probability of the event times its consequences as measured in some relevant unit (dollars, lives, etc.). More generally, the risk of an event is a vector of possible likelihood and outcomes (scenarios, etc.), each implying consequences on one or more dimensions.

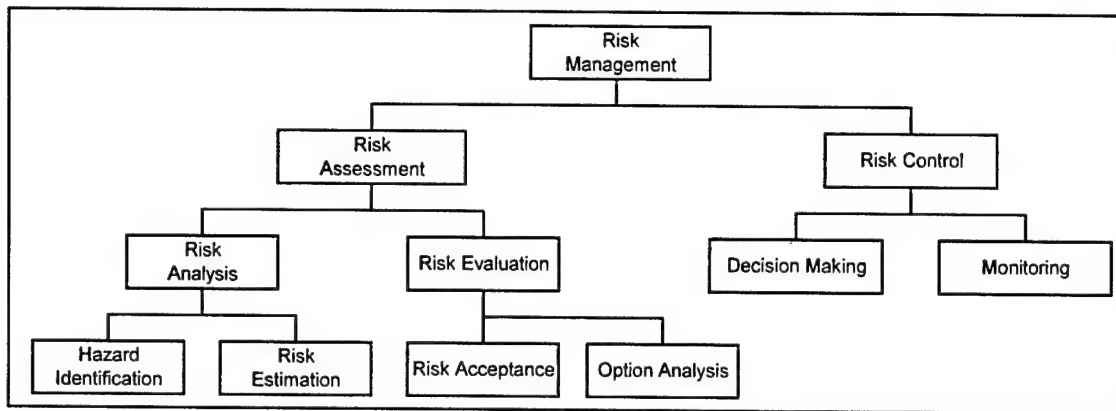


Figure 2-1. Framework of risk management, illustrating the role of risk assessment and risk analysis (after Canadian Standards Association 1991)

This ill-defined nature of the term hazard is, in fact, a benefit. The reason lies in the typical process of a major risk assessment that invariably begins with a *hazard identification* exercise. To avoid underestimation of the risk, it is important in a risk analysis to seek to obtain completeness, i.e., to identify *all* the reasonably likely scenarios, their probabilities, and their consequences. The experience and knowledge about most technical systems involves multiple disciplines and agents, e.g., designers and contractors, who might not be trained in risk analysis. It becomes important that the analyst extracts all the information he can from these sources by asking them, individually and through group exercises or brainstorming sessions, to list all the hazards they can think of. To facilitate this thinking process, the concept of a hazard must be loose. The threat or hazard to one man's system may be the result of an accident in another man's domain. Therefore, the identified hazards are collected from all the sources available in the terms that the providers are most comfortable with, and it becomes the risk analyst's job to make sense of it all.

The next task for the risk analyst is to identify the causes and effects of the hazards. Some hazards may already, in effect, be root causes, e.g., a flood on the river. What the root cause or *initiating event* is may in practice depend on the nature of the data available to the analyst (e.g., the particular form of the available accident statistics). Other hazards may be the result of one or more accident scenarios that lead to these states, i.e., that lead to major structural damage or project delay of one kind or another. *Consequence analysis* is the tracing (modeling) of the various possible results of the hazard. For example, a broken towline may cause reduced control, which in turn contributes to a collision, which in turn leads to damage to the dam segment, which is followed by sinking. The implications of all these potential scenarios in terms of injuries and economics are also a key part of the risk analysis.

A variety of tools exist to aid the risk analyst, including failure mode and effects analysis, fault trees, influence diagrams, event and decision trees, and structural reliability analysis. Most of these tools are designed to analyze the likelihood of various states of a technical system. The simplest set of such states is simply "fail-no fail." The analyst attempts to determine the *reliability* of a

system, subsystem, or operation as the probability that it will successfully perform its intended function. Therefore, the analyst must use all available information (data, mechanics, and other tools at his disposal) that is useful to achieve the analysis objectives.

The complete study of the technical system will include the identification and analysis of various options to reduce the likelihood or mitigate the risk (consequences and their likelihood) of the various hazards.

The risk evaluation of the various hazards will include consideration of their importance and their "tolerability," perhaps by comparing them with industry or regulatory standards (expressed in terms of, for example, expected number of fatalities per 10,000 man-hours of work) or perhaps through cost-risk-benefit analyses to evaluate the effectiveness of alternative mitigation strategies. Cost and benefits are perceived differently by the various stakeholders in risk management (dam owner, construction contractor, laborer, etc.), and the decision-maker must be sensitive to all parties involved, even if he directly represents only one of them.

These and other concepts and elements of risk management terminology, defined where they first appear, will recur throughout this document. It is the nature of the relatively young and dynamic field, however, that the terms used are not all universal. Where ambiguity might exist, this report generally follows the format and style of the Canadian Standards Association (CSA 1991).

## **2.2 Risk Analysis Methodologies**

A formal risk analysis of a construction project is a work process consisting of the following:

- Comprehensive description of the project (activities, schedule, locations etc.).
- Comprehensive identification of hazards to the project.
- Qualitative assessment of likelihood and consequences of the identified hazards.
- Separation of the significant hazards on basis of the qualitative risk assessment.
- More definitive quantitative analysis of the significant hazards (optional).
- Risk evaluation, i.e., comparison of the established quantified risk with predefined acceptance levels (optional).
- Identification and evaluation of risk reduction measures.
- Decision on desirable risk reduction strategies.
- Recursion of the process until the risks for the project are acceptable.



The more definitive *quantitative analysis* of the significant hazards is noted to be optional because it may not be required to facilitate the necessary decisions concerning risk reduction measures and acceptance of the project quantified risk. The *risk evaluation* is also noted optional because formalized acceptance criteria may not be available or even practicable. Deciding that a risk level is acceptable can be based on the conclusion that all practicable and affordable precautions have been made and that a further reduction of the risk would require excessive additional cost.

A diagram illustrating the procedure is shown as Figure 2-2.

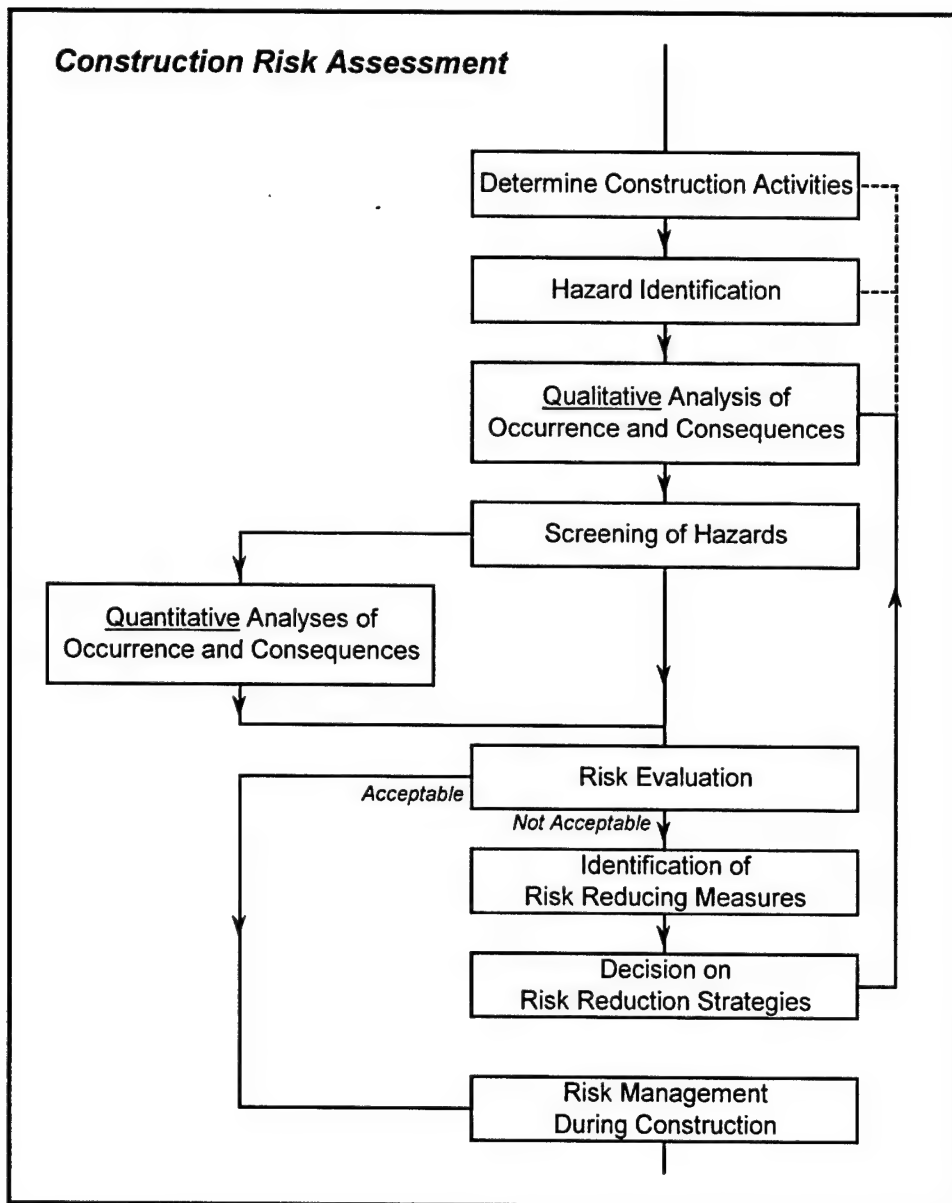


Figure 2-2 Risk assessment methodology logic chart

## 2.2.1 Identification of hazards and risks

Identification of hazards and their associated risks is the most important element in a risk analysis. This task element combines experience with imaginative skills into a systematic approach to identify events or conditions that would have a significant influence on the project.

A detailed description of the project (including construction activities, schedule, locations, and conditions) provides the basic framework for the identification process. The quality of the brainstorming session and the resulting coverage of the hazards identified will be governed by the quality of the project description. Personnel familiar with the details of the project possess knowledge that is essential for performing an acceptable hazard identification. However, due to their involvement in the project, they have performed a more or less formalized hazard identification during development of the project and may have a tendency to focus on the same issues in the hazard identification process during the formal risk analysis. It is therefore important that their knowledge about the project is communicated to the risk analysis team. This will ensure that the entire team is well informed about the project and able to make relevant supplements to the hazards identified. Discussion of the project in detail is mandatory for a thorough recognition and clear identification of hazards.

A systematic structuring of the brainstorming process can be achieved by establishing a list of hazard categories that can be considered. Examples of such categories are

- *External or internal (offsite or onsite).*  
A hazard may originate from an event or condition either outside or inside the project. Hazards within the project normally offer some possibility of active control or prevention whereas external hazards typically have to be dealt with by passive means (observation and protection).
- *Accidental or intentional (planned).*  
A hazard may be the result of an accidental, unforeseen, or unwanted event as opposed to an unwanted result of an intentional activity or action. The characteristic difference is that the occurrence of accidental events can be reduced by increasing awareness about the hazards and by more carefully prepared work procedures. The unwanted result of an intended activity (i.e., a consequence due to design errors or to deviation between assumed and actual conditions) is more difficult to handle because the personnel involved normally approach planned activities with confidence.
- *Condition or event.*  
The hazard may be a condition that makes an activity or situation in the project particularly hazardous, or it may be a particular event or action that in itself presents a hazard. A hazardous condition could typically be an adverse environmental condition such as a strong wind. A hazardous event could be failure of some equipment used in construction such as a ballast pump or a wire rope or cable.

Additional categories or systematic groupings can be proposed on a project-unique basis. Hazards associated with innovative construction methods can be categorized. This pre-brainstorming organization is generally recommended to ensure thorough and structured brainstorming sessions.

The outcome of the hazard identification sessions is structured and documented to permit review and correction of the findings. A sample master list for the Braddock Dam project is presented as Appendix A. This final listing provides a basis for the subsequent risk estimation process or processes.

### 2.2.2 Qualitative risk analysis

A qualitative analysis of the risk will normally proceed for each hazard identified. If the hazard identification has been adequately broad and comprehensive, the identified hazards will include some hazards that do not present significant risks. A qualitative evaluation of the hazards is therefore performed as an initial screening to eliminate hazards representing a risk sufficiently low to exclude them from further consideration in the quantitative analysis. In some situations it may not be necessary to go beyond the qualitative risk analysis to make the appropriate decisions on risk reduction and acceptance.

In a qualitative risk assessment, the frequency of occurrence and the extent of the consequences are expressed in terms of classes, typically three to five. Each class is associated with a numerical range and a qualitative label. An example is shown in the Tables 2-1 and 2-2.

<b>Table 2-1</b> <b>Examples of Occurrence (left) and Consequence (right)</b> <b>Classifications to Be Adopted in a Qualitative Risk Analysis</b>			
Occurrence Class	Frequency of Occurrence	Consequence Class	Consequence
Low	"<0.01 per year" or "Less than 1 occurrence per 100 projects"	Low	"<\$100,000" or "Less than 5 injuries"
Medium	"0.01-1.0 per year" or "More than 1 occurrence per 100 projects, but less than 1 occurrence per project"	Medium	"\$100,000-\$1 million" or "More than 5 injuries but fewer than 2 fatalities"
High	">1.0 per year" or "More than once per project"	High	">\$1 million" or "More than 2 fatalities"

Using the qualitative classification of occurrence and consequences, the risk level (i.e., the combination of occurrence and consequence) fits into a convenient matrix form:

<b>Table 2-2</b> <b>Example Risk Table Associating a Qualitative Risk Level with</b> <b>Different Combinations of Occurrence and Consequence</b>			
Consequence	Low	Medium	High
Occurrence	Low	Medium	High
Low	Very low	Low	Medium
Medium	Low	Medium	High
High	Medium	High	Very high

An established scheme is used to evaluate the risk occurrence and consequences for each hazard. This scheme should be defined and explained in a document to ensure consistency in evaluations by different people. The qualitative evaluation will typically be based on

- Experience.
- Engineering judgment.
- Readily available statistics.
- Inductive reasoning.

The result of the qualitative risk analysis will provide an overview of the risk evaluation that can be used to help determine risk reduction measures or further quantitative analysis.

If the risk assessment is to be taken further in detail to a quantitative analysis, a screening process is used to focus the effort of the more detailed and elaborate analysis on the hazards that dominate the qualitative risk picture. A typical screening method is to exclude hazards associated with qualitative risks in the *very low* or *low* categories of combined occurrence and consequence.

<b>Table 2-3</b> <b>Strategy for Screening Hazards to Be Considered in Quantitative</b> <b>Risk Analysis</b>			
Consequence	Low	Medium	High
Occurrence	Low	Medium	High
Low	Very low	Low	Medium
Medium	Low	Medium	High
High	Medium	High	Very high

If more than one type of consequence is considered (cost, delay, human injury, environmental impact), the screening of a given hazard should be done individually for each type of consequence. Hence, a hazard can qualify as significant to be included in the quantitative analysis on basis of one or more of the consequence types. In the quantitative analysis, it will thus be relevant to focus on the detailed consequence estimation of those consequences that caused the hazard to qualify.

### 2.2.3 Quantitative risk analysis

The risk analysis may proceed to the quantitative stage based on the outcome of the screening process and the purpose of the risk evaluation. In the quantitative analysis stage, event and fault trees provide a general framework for probabilistic risk analysis. The *event tree* is a tool used to break down the development of a specific hazard or situation into well-defined scenarios. A discussion of event tree construction is given below. A fault tree is intended to represent the logic and track the calculation of the probability of occurrence of a specific unwanted event or situation. For a description of fault trees and other methods and relevant tools, reference can be made to several standard texts (e.g., Henley and Kumamoto 1981).

The construction of an event tree is straightforward. An event tree represents an ordered sequence of possible events. Each stage in the sequence may have one or more possible outcomes, typically characterized by a discrete set of alternatives. The branching point at which a new set of alternatives is introduced is called a *node*.

To exemplify the concept of event trees, the loss of towboat propulsion during the final tow from the outfitting pier to the damsite is considered. At the outfitting pier, the tow (segment and tug) will be aligned parallel to the current with the tug pushing downstream. When the tow has reached the middle of the river and is about 1,000 ft (35 m) downstream from the outfitting pier, the tow is rotated 180 deg and continues, backing down to the damsite, as shown in Figure 2-3.

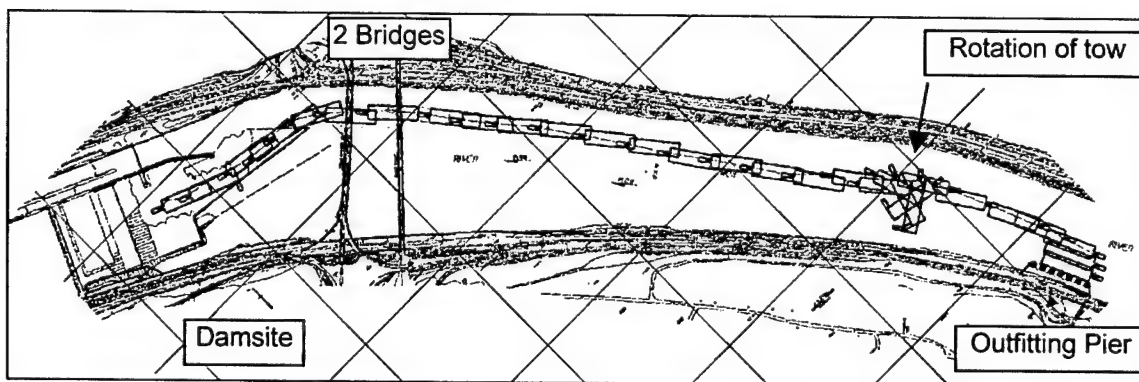


Figure 2-3. Illustration of final tow of the segment from outfitting pier (right) to damsite (left)

If the propulsion on the main tug is lost, the tow will drift with the current toward the bridges and lock (i.e., from right to left in Figure 2-3). If control is not regained the tow may ground, collide with a bridge, or collide with the midstream lock wall. Assessment of the sequence in terms of an event tree is shown in Figure 2-4. The leftmost state represents the initiating event, loss of propulsion. The branches emanating from the first node represent two possible tow locations, upstream or downstream of the bridges. The second set of nodes contains branches reflecting the successfulness of emergency engagement of the auxiliary tug, and the third set of branches defines the development of the scenario as to how and where the tow is finally stopped.

Initiating event	Location relative to bridges	Auxiliary tug engagement	Type of contact	Consequence: Damage to tow		
Loss of propulsion P=0.001	Upstream P=0.667	Successful P=0.333		Under control P=2.2e-4	None	
		Not successful P=0.667	Grounding P=0.333	Grounding P=1.5e-4	Small	
			Collision to bridge P=0.667	Collision P=3.0e-4	Large	
	Downstream P=0.333	Successful P=0.050		Under control P=1.7e-5	None	
		Not successful P=0.950	Grounding P=0.050	Grounding P=1.6e-5	Small	
			Collision to lock wall P=0.950	Collision P=3.0e-4	Medium	
	<b>Summary</b>					
	Consequences		Probability			
	None		0.00024			
	Small		0.00016			
Medium		0.00030				
Large		0.00030				
Sum		0.00100				

Figure 2-4. Illustration of event tree for event of loss of propulsion during the final tow

Note that the selection of the nodal events for branches and the discrete number of alternatives or branches is a typical engineering modeling problem that involves engineering judgment as to the relative benefits of coarser versus finer modeling.

Numbers indicating probabilities are attached to the various branches. The number on the leftmost state is the probability that the initiating event, here a loss of propulsion, will occur during the tow. This probability is determined as the duration of the tow multiplied by the mean rate of loss of propulsion.<sup>1</sup> The mean rate may be estimated from actual statistical data, preferably for a subset of tows or towboats that are representative of those under consideration. The numbers attached to subsequent branches define the branch probabilities, conditional on

<sup>1</sup> For the unusual or extreme events of typical interest, the mean annual rate is much less than 1, and so it is also approximately the annual probability of the event, the probability of two or more such events being effectively zero. In practice, therefore, the use of annual probability and mean annual rate is often interchangeable.

the outcomes of previous branches in the tree. The sum of the probabilities in one branch should always sum to 1.0.

Determination of event tree branch probabilities may be the result of estimates using engineering judgment in the absence of extensive occurrence databases. In the example tree, the relative likelihood of the tow being upstream or downstream of the bridges at loss of power is based on the length of the two parts of the tow route (upstream of bridges: 0.667; downstream of bridges: 0.333). Engagement of the auxiliary tow is estimated to have a 33 percent chance of being successful if the tow is upstream of the bridge and only 5 percent if downstream of the bridges. The difference results from the limited length available downstream for the engagement. Finally, the probability that the resulting type of contact is grounding rather than collision is estimated at 33 percent when upstream and only 5 percent when downstream. (Note that assignment of branch probabilities in an event tree may be aided by fault tree analyses.)

An event tree path starting from the original node flowing through a sequence of branches to the right-hand side constitutes one unique scenario. For example, in the tree of Figure 2.4, one such scenario is {Loss of propulsion, Upstream of bridges, Unsuccessful auxiliary tow engagement, Grounding}. The leaf or end point of each path in the event tree carries a description of the outcome of the scenario. It may be as simple as system success or failure (i.e., the tow is successful or not) or it may represent measures of the consequences of the scenario in the form of a vector of outcome attributes (e.g., dollars and lives lost). In Figure 2.4 the outcomes are defined in terms of damage to the segment: None, Small, Medium, and Large.

The displayed probability of each branching event or condition is conditional on the occurrence of events that precede it in the tree. Therefore, the joint probability of the intersection of events that constitute a scenario is found by simple multiplication. For example, for the scenario {Loss of propulsion, Upstream of bridges, Unsuccessful auxiliary tow engagement, Grounding}, the probability is

$$0.001 \times 0.667 \times 0.667 \times 0.333 = 0.00015$$

The implied damage is "Small." Determination of small damage in terms of quantitative consequences is done in a consequence analysis for the specific scenario.

Note that the total probability of any particular consequence category can be found by summing the probabilities of all scenarios that lead to that outcome. So, the probability of scenarios with only small damage consequence associated with the frequency of grounding is the sum of the probabilities of the second and fifth scenarios: 0.000164. Eliminating the probability of the initiating event, estimated as 0.001 in this example, it follows that small damage consequence is expected to occur with a probability of 16 percent if propulsion is lost.

Event trees can include the notion of time and multiple “levels” of branches (not just binary or Yes-No). They facilitate dealing with lack of independence, i.e., the conditional probabilities of one event given another. Further, one may include a continuous spectrum of branches at a node, usually graphically represented by a “fan” originating at the node. There need not be a temporal order to the sequence of branches, but it is common to do so.

What event trees do not do well is “functional analysis.” This means that at the end of a scenario, event trees do not provide a formal means of determining whether that particular conjunction of events leads to system failure or not. Therefore, unless it is obvious by inspection, one may need to use other tools, such as a block diagram or fault tree (both of which display the logic of the system relative to the parts) or a structural analysis, or some other technique of engineering analysis in conjunction with an event tree to determine the outcome of each of the scenarios whose probability of occurrence is analyzed by the event tree.

## **2.3 Example Project Description—Braddock Dam**

The objective of the Braddock Dam construction project is the construction of a replacement dam for the existing fixed-weir dam at Lock and Dam 2 on the Monongahela River, located as shown in Figure 2-5. The new dam is a tainter-gated dam located immediately upstream of the existing dam weir, as shown in and Figure 2-6 and Figure 2-7. It will extend from the existing lock river wall across the river to a previously constructed weir wall.

Innovative construction techniques are adopted for the submerged part of the dam structure. The sill and lower pier structure will be prefabricated in a precasting basin, floated and transported as a huge barge to the site, and installed on drilled shafts at the damsite. This approach eliminates the need for the extensive temporary cofferdam that traditionally is used to facilitate construction of the dam components in the dry below water level.

In relation to the risk analysis, some qualitative characteristics can be highlighted for the innovative float-in method as compared to the in situ construction method using a cofferdam:

- The structures go through many different stages of partial completion and different conditions: dry, floating, towed, moored, submerged. Each situation is associated with certain anticipated loads and involves exposure to potential unwanted loads (impact, grounding).
- The tow and float-in operations require optimization of the weight of the floating structure and thus of the temporary structural dimensions such as wall thicknesses. Thus, there is limited opportunity to provide the floating structures with robustness toward unforeseen loads, design mistakes, and construction errors.



- Large structures are relocated during the project. They will be exposed to various hazards and, because of the large investments (cost and time) they represent, the consequences of those hazards can become large.

These different stages and conditions imply that the designer has to consider more situations in the development and verification of the design. The extended design process will increase the potential for simple errors, omissions, and overlooked scenarios. The different stages and situations require the contractor to make more detailed activity and contingency plans.

These qualitative characteristics should be realized and addressed by “higher than normal” emphasis on the quality of design work and on planning of construction activities and contingency situations. In the course of the present study, the impression is that this has been achieved on the Braddock Dam project.



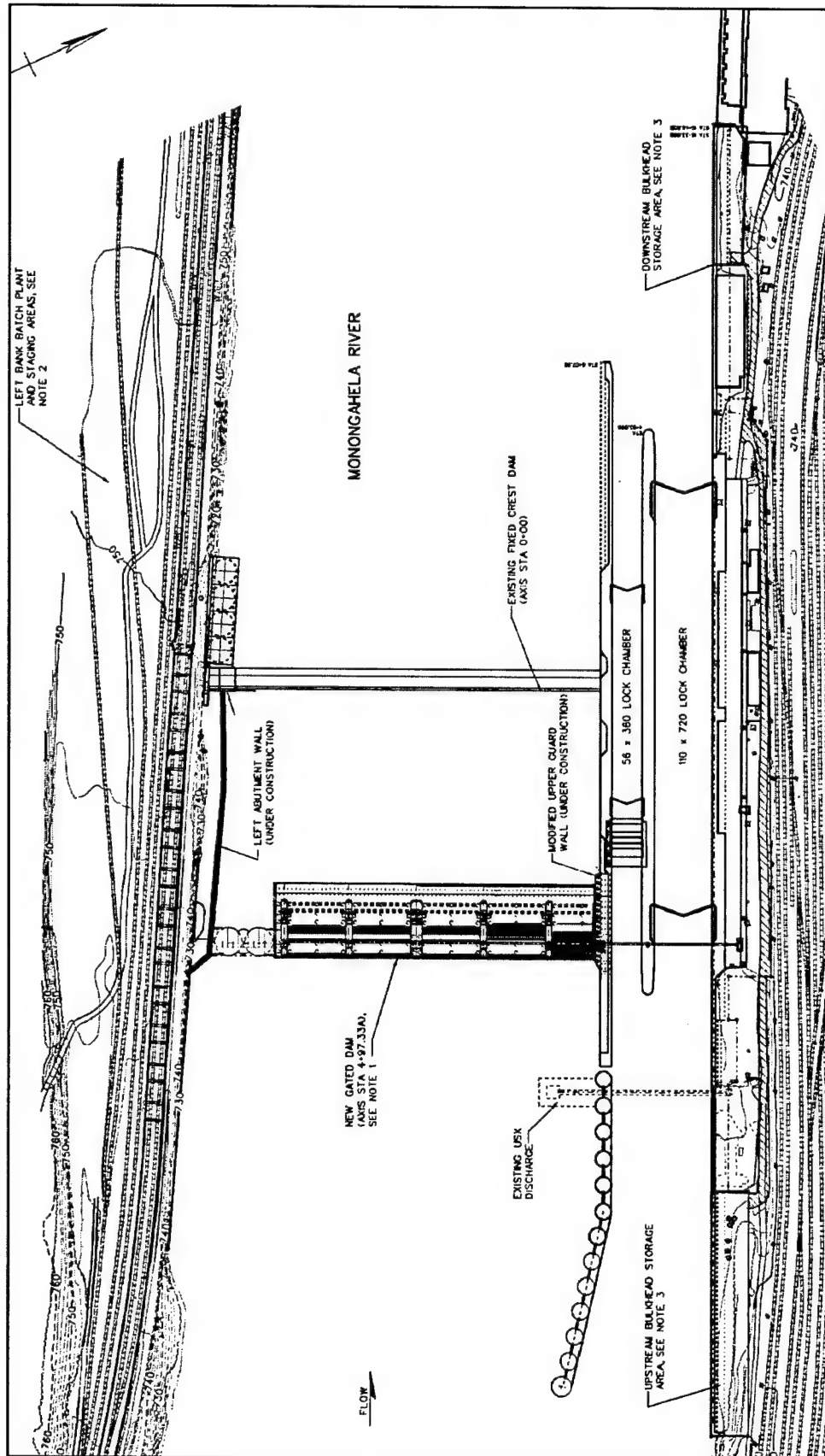


Figure 2-6. Location of new dam to be constructed upstream from existing Lock and Dam 2

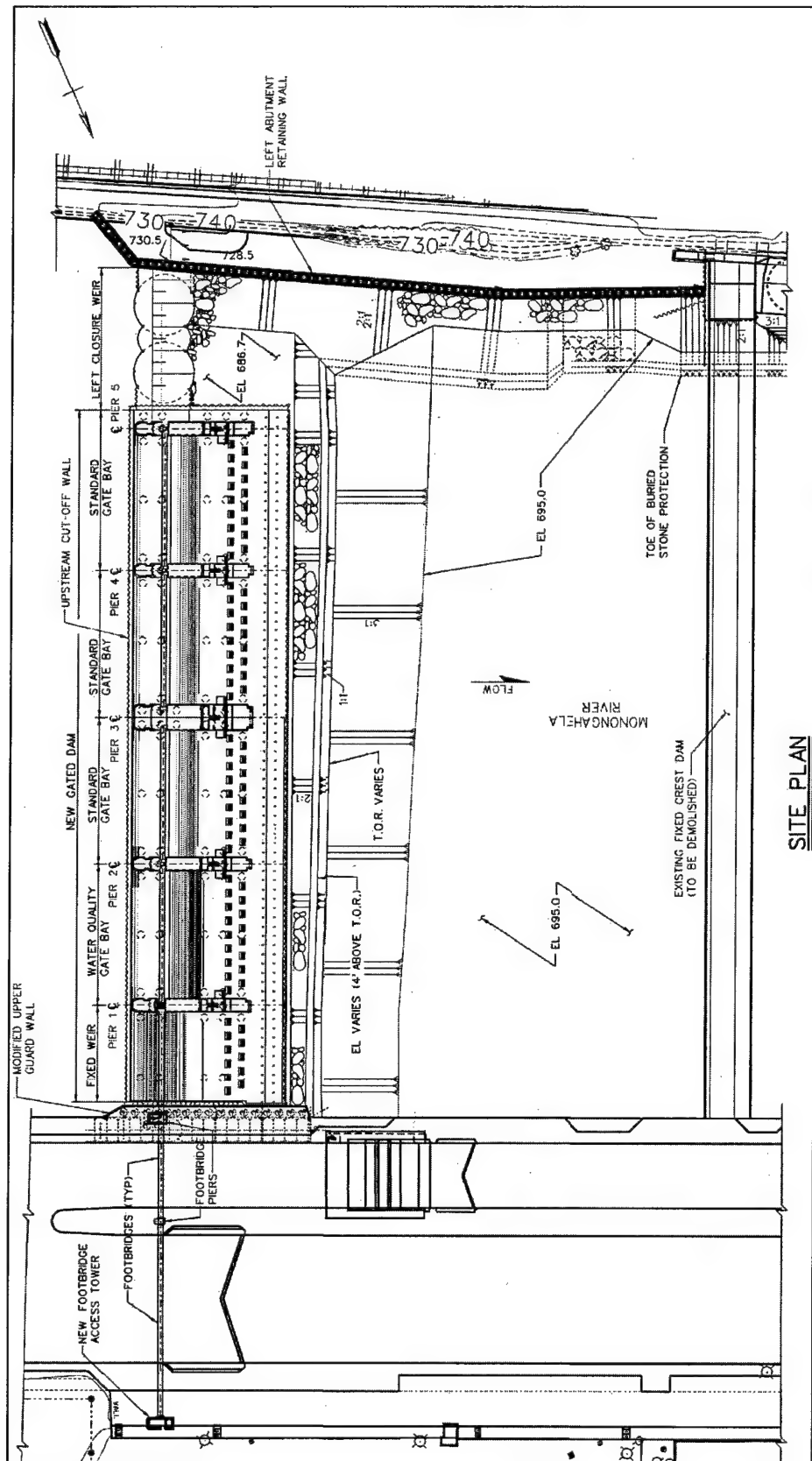


Figure 2-7. Braddock Dam

## **3.0 Braddock Dam Risk Assessment Study**

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### **3.1 Construction Sequence Phases**

In accordance with the methodology summarized in Section 2.1, the risk analysis is introduced by identifying and describing the construction activities in the project. The main activities are

- Initial planning, procurement and preparations.
- Prefabrication of dam segments.
  - Prefabrication in precasting basin.
  - Launching and float-out.
  - Tow/transport to outfitting pier.
  - Outfitting.
  - Tow/transport to damsite.
- Fabrication of maintenance bulkheads.
- Fabrication of tainter gates.
- Damsite activities.
  - Preparation of dam foundation.
  - Setdown of prefabricated dam segments.
  - Grouting and infill of prefabricated dam segments.
  - Installation of prefabricated tailrace segments.
  - Completion of pier structures.
  - Installation of tainter gates.
  - Tainter gate seals adjustment and closure pours.
  - Construction of closure weir.
- Demolition of existing dam.
- Restoration of sites.

A graphic summary of the project is given in Figure 3-1 illustrating the locations and approximate temporal relationships of the main activities. The following text subsections give a short description of the project activities. A more precise listing of the construction activities and events, which is used as reference throughout this risk analysis, is provided as Appendix A.

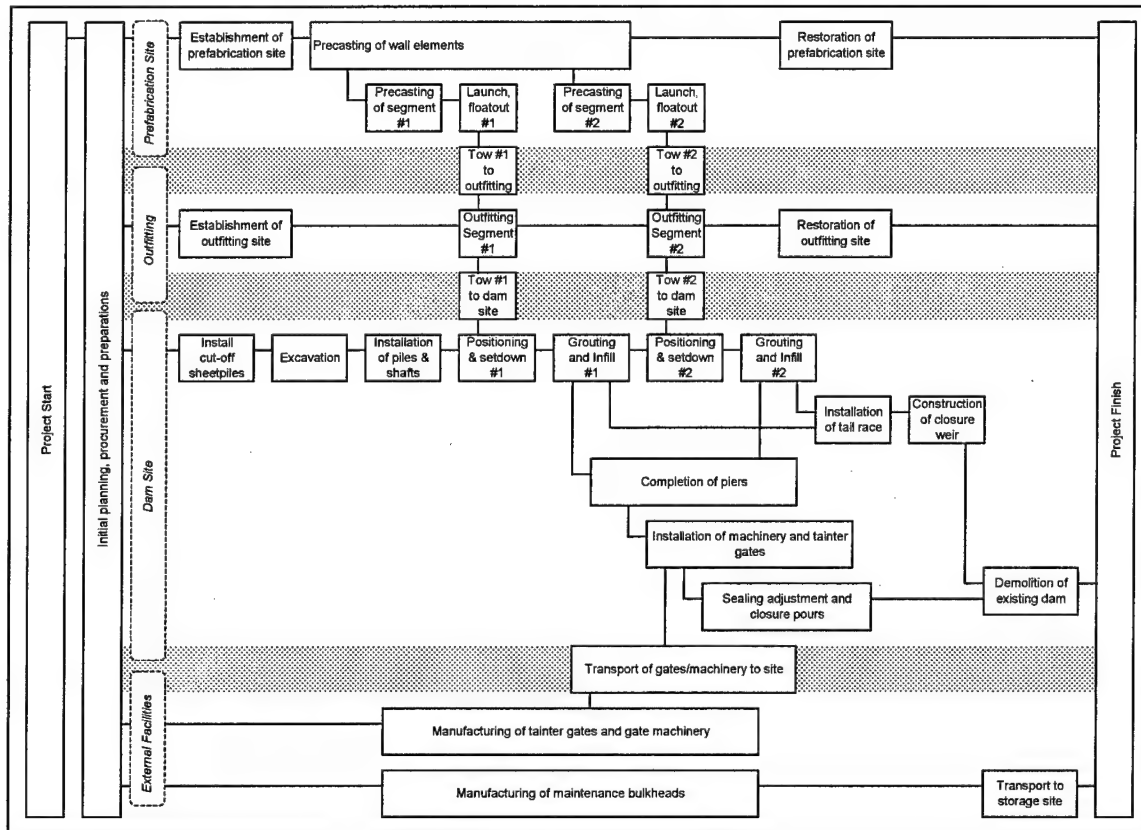


Figure 3-1. Overview of project activities

### 3.1.1 Initial planning, procurement, and preparation

These events include the activities related to the planning and design of the dam prior to the award of the construction contract. The type of design and construction contracts, the division of responsibility between architect/engineer and construction contractor, and the required completeness of the drawings and specifications are significant parameters for these activities.

### 3.1.2 Prefabrication of dam segments

The submerged part of the dam is divided into two large segments:

- Segment 1: largest segment (333 ft, 1 in. × 106 ft, 2 in.) (105 × 32 m) with three bays (fixed-weir, water quality, and standard gate bay).
- Segment 2: smallest segment (249 ft, 1 in. × 106 ft, 2 in.) (76 × 32 m) with two standard gate bays.

The segments are prefabricated on a site in Leetsdale, PA, located on the Ohio River downstream from the damsite. The prefabrication site consists of excavated basins—one deep and one shallow—that permit the segments to be assembled in the dry and launched into the Ohio River by a controlled progressive flooding of the basins.

The segments are shell structures with closed compartments to provide buoyancy and stability during towing, ballasting, and final setdown. To obtain sufficient buoyancy, the bays between the prefabricated piers are closed with temporary bulkheads to allow dewatering of the bays. These bulkheads are also used for dewatering of the bays at site, when the final adjustment of seals is done and the closure pours are made.

When completed for installation, i.e., just prior to setdown, the segments will have a draft of approximately 15 ft (4.6 m). Sufficient river depth for this draft cannot be assured along the tow transport route from the prefabrication basin to the damsite for lower-bound riverflows. Consequently, each segment prefabrication is staged such that most of the segment is built in the dry precasting basin in Leetsdale. The fabrication of each segment will be limited but complete enough to ensure flotation at a maximum draft of approximately 11 ft (3.4 m). Each semicomplete segment will be towed to an area slightly upstream from the damsite referred to as an outfitting pier. The segment is moored at the outfitting pier, and the remainder of the segment construction necessary for installation is completed. The equipment and temporary structures necessary for the final tow, positioning, and setdown are installed.

From the outfitting pier the segment is towed to the damsite and positioned for setdown. The water depth for the approximately 2 miles (3.2 km) between the outfitting pier and the damsite is sufficient for an approximate 15-ft (4.6-m) draft.

**3.1.2.1 Establishment of the precasting basin.** Development of the prefabrication basin site includes driving of sheet piles to seal off the basin from the river, dewatering the site, and finally, excavating the basins. The sheet-pile arrangement isolating the basin from the river will include a braced sheet-pile wall arrangement that allows a channel to the river to be opened for float-out of Segment 1 and then allow the basin to be closed again for construction and launching of Segment 2.

**3.1.2.2 Prefabrication in the precasting basin.** The float-in segments are produced as an assembly of prefabricated slabs, walls, and shells. A concrete plant adjacent to casting and curing beds will be used to prefabricate the individual components. The components are then transported from the prefabrication facility to the assembly area in the precasting basin along a route of approximately 300 to 400 yd (275 to 365 m).

The segments are assembled on the bottom of the shallow basin that is above the water level of the river. The construction sequence for each segment is as follows:

- Erect the precast panels.
- Cast the bottom slab.
- Post-tension the slab.
- Cast the panel closures.
- Install temporary bracing inside shells.
- Form and cast top slabs.
- Place ballast concrete.
- Install downstream bulkheads.
- Install temporary ballast system.
- Install mooring and towing brackets.
- Install downstream grout bags.

**3.1.2.3 Launching and float-out.** To launch the finalized segment, the basin is flooded and the water within the basin is raised to a level that is 15 ft (4.6 m) above the river stage. The segment then comes afloat from its rest at the shallow basin and is towed to the deep basin. The water level is then lowered to the river stage. When the conditions are appropriate for launching, the dike to the river is opened and the segment is towed out of the basin.

Segment 1 is the first to be completed and will be launched first. The channel will be closed again and the basin dewatered so that construction of Segment 2 can commence or continue. When Segment 2 is ready to go to the outfitting pier, the same launch procedure is followed. Launching of Segment 2 will not start before Segment 1 is positioned at the site. Up to 6 months may separate launching of the two segments.

**3.1.2.4 Tow to outfitting pier.** The tow from the segment production site at Leetsdale to the outfitting pier 1 mile (1.6 km) upstream of the site covers 15 miles (24 km) along the Ohio River (to Pittsburgh Point) and approximately 12.2 miles (19.5 km) along the Monongahela River. The tow will pass three locks and 20 bridges, as detailed in Table 3-1. The tow is planned to take 16 hr and will require three tugs. The transit will end by mooring of the segment at the outfitting pier. The draft of the segment is approximately 11 ft (3.4 m).



**Table 3-1  
Obstacles Along Tow Route from Precasting Yard to Outfitting Pier**

Mileage	En route feature	Navigation Opening, ft
+15.0	Start: fabrication yard at Leetsdale	
+13.3	<i>Dashields Lock and Dam</i>	110
+11.8	Sewickley Highway Bridge	724.0 × 73.4
+8.7	Interstate 79 Highway Bridge	725.0 × 68.0
+6.2	<i>Emsworth Locks and Dams</i>	110
+3.3	Pittsburgh-McKees Rocks Highway Bridge	750.0 × 100.6
+2.4	Ohio Connecting Railroad Bridge	508.0 × 67.9
+0.8	West End – North Side Highway Bridge	755.0 × 66.3
-0.2	Fort Pitt Highway Bridge	640.0 × 47.1
-0.7	Smithfield Street Highway Bridge	344.0 × 42.5
-1.0	Port Authority Transit Bridge	351.0 × 43.9
-1.1	Liberty Highway Bridge	448.0 × 44.4
-1.4	South Tenth Street Highway Bridge	705.7 × 50.3
-2.3	Birmingham Highway Bridge	607.0 × 64.8
-3.1	Monongahela Connecting Railroad Bridge	311.0 × 48.4
-5.9	Glenwood Highway Bridge	557.0 × 50.0
-6.1	CSX Trans. Railroad Bridge	453.0 × 50.5
-7.2	Homestead Hi-level Highway Bridge	516.3 × 51.2
-8.5	P. & L. E. Railroad Bridge	250.0 × 51.6
-9.3	Union Railroad Bridge	483.0 × 50.8
-9.5	Rankin Highway Bridge	505.3 × 45.0
-11.2	<i>Locks and Dam 2 (Braddock)</i>	110.0
-11.5	Union Railroad Bridge	378.0 × 55.2
-11.6	Conrail Railroad Bridge	393.0 × 45.6
-12.2	End: Outfitting pier at Duquesne	

**3.1.2.5 Outfitting.** Outfitting of the segment involves casting of additional concrete for the completion of slabs, placing of additional concrete to extend pier walls to el 726, and installation of equipment required for positioning, setdown, base grouting, and structural infill. Work tasks include construction for the following:

- Tremie guide sleeves.
- Temporary work deck.
- Ballast system.
- Horn guides for positioning.
- Winches.

- Upstream bulkheads and additional downstream bulkheads.
- Flat jacks for leveling.

After outfitting, the segment will have a draft of approximately 15 ft (4.6 m).

**3.1.2.6 Tow to damsite.** The tow of the segment to the damsite involves release of the outfitting pier mooring, towing the segment approximately 1 mile downstream to the damsite, and mooring of the segment for the final positioning and setdown. The allocated time window is 24 to 48 hr.

The tow passes the last two bridges on the route from the precasting yard to the outfitting pier, as listed in Table 3.2.

<b>Table 3-2</b>		
<b>Obstacles Along Tow Route from Outfitting Pier to Damsite</b>		
<b>Mileage</b>	<b>En Route Feature</b>	<b>Navigational Opening, ft</b>
-12.2	Start: outfitting pier at Duquesne	
-11.6	Conrail Railroad Bridge	393.0 × 45.6
-11.5	Union Railroad Bridge	378.0 × 55.2
-11.2	End: site for Braddock Dam and Locks	
Note: To convert miles to kilometers, multiply by 1.609347; to convert feet to meters, multiply by 0.3048.		

### 3.1.3 Production of maintenance bulkheads

The project also includes fabrication of maintenance bulkheads for the tainter gate bays and transportation of those to a dedicated storage yard. The bulkheads may or may not be used during construction for dewatering of a tainter gate bay.

### 3.1.4 Damsite activities

**3.1.4.1 Preparation of foundation.** The foundation for the segments consists of an excavation bounded by cutoff walls up and downstream of the segment position. Drilled shafts and driven H-piles are installed inside the excavation, and the bottom of the excavation is finished with a screeded gravel base. All of the foundation preparations are performed in the wet before arrival of the segments.

Just prior to launching of the segment from the outfitting pier, the subgrade at the site is prepared for setdown. This involves resounding, removal of any siltation by suction pump, and installation of inflatable fabric bags for subdivision of the underbase grouting area.

**3.1.4.2 Positioning and setdown.** The segments are towed by tugs to the dam position and are aligned parallel to the current. Segment 1 will be positioned

with its center above the axis of the dam while Segment 2 initially is positioned and aligned upstream from the dam axis.

The support tug is released from the segment while the main tug remains attached. The support tug runs mooring lines from the segment: four lines to upstream mooring piles, two lines to downstream anchors, and two to other mooring points (one on land and one on the lock river wall).

Once the mooring lines are connected, rotation of the segment is initiated and mooring lines are tensioned to take over control of the segment. When mooring lines are tensioned and positioning control using the lines is ensured, the main tug is released and the associated towing arrangements are removed.

Using the upstream and downstream mooring lines, the segment is rotated to align with the dam axis. Segment 2 is at this stage approximately 300 ft (90 m) upstream from the final position and will be winched downstream to the dam axis.

Using transverse mooring lines, the segment is shifted to the intended position parallel to the dam axis.

The setdown bracket is aligned over the horn guide. For Segment 1 the horn guide is mounted on the lock river wall; for Segment 2 the guide is mounted on Segment 1. The segment is ballasted to within 6 in. (150 mm) of grade, and final horizontal alignment is ensured using hydraulic rams acting on the neighboring structures.

The segment is set down resting on hydraulic flat jacks on six drilled shafts. The segment is leveled with the hydraulic system, and the flat jacks are grouted. Finally, the bays are flooded to provide and maintain a submerged weight on the segment of 10 to 20 percent of the segment weight.

**3.1.4.3 Grouting and infill.** Underbase grouting starts by inflating preinstalled transverse fabric bags with grout. This will subdivide the underbase void into manageable sizes. The downstream grouting bag is then filled to form a seal, and the grouting can commence one area at a time, starting at the downstream seal toward the upstream opening.

After completion of the underbase grouting, the flat jacks and sand jacks are removed. All bays are flooded to ensure loading of the underbase grouting, and the top of the drilled shafts are then grouted.

Infill of the segment compartments starts by placing tremie concrete in all compartments with piles. Then the downstream (low) compartments are completely tremied and a layer of 11 ft (3.4 m) of tremie is placed in the upstream (high) compartments.

The remainder of the infill concrete to be placed in the upstream compartments and in the piers is poured in the dry by 5-ft (1.5-m) lifts. The bay will be dewatered to permit this operation. Only one bay can be dewatered at a

time. All infill concrete has to be placed in Segment 1 before Segment 2 is floated in and positioned adjacent to Segment 1.

**3.1.4.4 Construction of tailrace.** A tailrace—essentially a downstream extension of the top slab of the downstream part of the segment—is to be constructed. Precast slabs are placed to rest on the downstream edge of the segment and on the downstream cutoff wall. The void beneath the slabs is filled with tremie concrete. The tailrace can be constructed at any time after both segments have been filled with concrete. Due to the interlocking arrangement of the precast slabs, the work has to commence sequentially from the river lock wall end of Segment 1 to the abutment side of Segment 2.

**3.1.4.5 Construction of piers.** The piers on the float-in segments have been completed to reach above water level when the segments are in place. Thus, completion of the piers can be done using in-the-dry concrete construction. The concreting work will be performed offshore. Prefabricated shells/walls are erected to form the outline of the pier, and infill concrete is placed where the structure is to be massive.

**3.1.4.6 Installation of tainter gates.** Tainter gates and gate machinery is installed when the concrete structure is completed. All structural concrete will be cured for at least 28 days before the tainter gates are installed.

The gates are prefabricated and will arrive completely assembled on a barge. During this process, the barge enters the bay, the gate is mounted to the trunnions, and the hydraulic actuators are attached. The gate is lifted off the barge using the hydraulic actuators, and the barge is floated out.

**3.1.4.7 Sealing adjustment and closure pours.** Up and downstream bulkheads are installed in the bay, and the bay is dewatered to allow adjustment of the sealing arrangement and placement of closure pours. Again, only one bay can be dewatered at a time.

**3.1.4.8 Construction of closure weir.** A fixed weir is used to close the dam from Segment 2 to the shore. The closure weir is constructed using circular sheet-pile cells filled with granular material and topped with a concrete cap. The closure weir is the last element to be constructed on the dam.

### **3.1.5 Demolition of existing dam**

Demolition of the existing dam will be associated with a permanent lowering of the water level in the pool between the new and the existing dam. This will lead to changes in the loading on the new dam, on the lock river wall and on the left abutment wall.

The stability of the left abutment wall will be ensured by installing a drainage system in the embankment and rock anchors to support the abutment wall. This system is installed and put into operation in parallel with the demolition of the existing dam.

The demolition is initiated by making a 5-ft (1.5-m) opening in the existing dam. This will lead to a slow dewatering of the pool between the two dams and will allow inspection of the effects on the lock river wall, the new dam, and the left abutment wall. In case of problems, the gates of the new dam will be opened to restore the water level in the pool.

After it can be determined with assurance that the dewatering will be safe, the contractor is given permission to continue demolition of the existing dam.

### **3.1.6 Restoration of sites**

Finally, all sites are to be restored.

## **3.2 Hazard Identification**

A sequence of hazard identification brainstorming sessions were held using the project description and the main activity list presented in the previous section as a basis for initial reference. Braddock Dam design engineers and senior engineers with broad experience in marine structures design and construction activities participated in those sessions, together with the risk analysis team. The team assembled for these sessions consisted of staff personnel with a variety of backgrounds, as detailed below.

### **Braddock Dam Study—Hazard Identification Team:**

*Ben C. Gerwick, Jr.*

Principal, Ben C. Gerwick, Inc.; Professor, University of California  
Experience: 55 years with marine construction

*C. Allin Cornell*

Research Professor, Stanford University  
Experience: 40 years teaching Probability Theory

*Robert B. Bittner*

Chief Engineer, Ben C. Gerwick, Inc.; Braddock Project Engineer  
Experience: 32 years with marine construction

*Neil J. Tuholski*

Senior Structural Engineer, Ben C. Gerwick, Inc.  
Lead Engineer, Olmsted Dam-Navigable Pass Section  
Experience: 32 years with ship, heavy industrial, and marine structures

*Henrik Gluver*

Senior Engineer

Experience: 14 years with research and development, risk analysis,  
and probabilistic analyses

As an introductory exercise for the participants not familiar with the concepts of hazard identification and to initiate discussion, a large sample of hazards (ranging from more to less obvious) was initially suggested by the risk analysis team.

Several sessions were held, and the results of each session were amended and documented in the hazard summary (Appendix A). The hazard summary documentation was used as input for each successive session.

Various techniques were used in the sessions to ensure sufficient coverage when possible. The participants were guided to consider and identify special elements, situations, or conditions on the basis of a generalized/qualitative description. Illustrations are described below.

- A segment in the construction work possesses large momentum and energy (kinetic due to movement, potential due to elevation) and can therefore cause a large amount of damage if this energy is unintentionally released or transferred.  
[Examples: During towing, a segment possesses a large kinetic energy.)
- A part of the construction work is exposed to extreme environmental conditions.  
[Example: A segment moored at the outfitting pier will be exposed to flood situations.]
- Completion of a certain operation relies on unique equipment or personnel. Malfunction of or damage to the equipment or incapacitation of the person is a hazard for the operation. Unavailability of equipment/person incurs delay or forces the contractor to use less suited equipment or less qualified personnel.  
[Example: Winches used for final positioning; ballasting control systems; tug officers trained for the tow operations; etc.]
- The load applied to a structure can change significantly from the conditions used for design during a particular operation. This can initiate a structural failure.  
[Example: During outfitting, the draft of the segment may increase beyond the draft used for design checks, and the hydrostatic load on various components of the structure could consequently rise beyond the design pressures. A similar condition may occur during the final setdown operation when the mass of the structure and the hydrodynamic added mass both increase.]
- Certain tasks of a work or contingency procedure are essential for the quality or safety of the structures. Incomplete execution or omission of

those tasks can present a hazard. Procedures that are not frequently used, such as contingency procedures, are prone to these discrepancies.

[Example: Release of the lines mooring a segment to the outfitting pier must be implemented in a flood situation. Inadequate release of these lines could cause the segment to be flooded when the river rises.]

- Loss of utilities or continuous deliveries.  
[Example: Loss of power in the final setdown phase. Loss of concrete delivery during tremie concreting.]
- Certain extreme conditions that pose an obvious hazard have been addressed extensively, but the opposite situation may also present a hazard.  
[Example: Flooding is of concern for the project and has been addressed, but insufficient water level may be a problem during the tow.]

In the quantitative analysis of the identified hazards, the risk analyst will develop a deeper and more detailed understanding of the governing conditions, procedures, and sequences for the activities exposed to the hazard. Additional hazards are likely to be realized in this work. Furthermore, decisions may be taken on the project that will eliminate some hazards. Thus, the hazard list will normally be developing continuously during the risk analysis work.

A qualitative analysis and the following screening of the hazards identified for the Braddock Dam project have not been thoroughly performed within the present study. If performed, the analysis would be done by the same method as the hazard identification utilizing the expert brainstorming sessions and would follow the general guidelines given in Section 2.2.2.

### **3.3 Quantitative Analysis**

A complete quantitative calculation of the risk associated with all the identified hazards for Braddock Dam is not within the scope of the present study. Selected hazards have been subjected to a quantitative analysis to illustrate the general guidelines on quantitative risk analysis given in Section 2.2.2. From the group of hazards with potentially large consequences (loss of a segment), specific hazards were selected for quantitative analysis to illustrate various calculation methods. The selected hazards are:

- Engineering design inadequacy.
- Construction engineering problem with potential for severe damage or loss.
- Construction contractor problem with potential for severe damage or loss.
- Collision with a bridge pier during tow of segment.

- Grounding of a segment during tow.
- Contingency mooring failure at the outfitting pier during high river stage.
- Segment floats over the outfitting pier during high water and is damaged when the river stage drops.

The analyses are documented in Appendix B. Examples of the techniques used to calculate the occurrence frequencies and consequences are discussed in the following sections.

### **3.3.1 Probabilities of occurrence**

Calculation of the probability of occurrence is generally found to be the most complex part of the quantitative risk analysis. The diversity of the identified hazards uses different modeling and calculation approaches based on the statistical data available. This is true in particular for construction projects that involve many different types of activities and processes and are exposed to different types of interaction with the surroundings. A risk analysis of a well-defined production facility will offer better opportunities for establishment of standard statistics and calculation methods. Another method that can be used to estimate probabilities of occurrence and cost/consequences is Expert-Opinion Elicitation (EOE). This method originated from the Delphi Method but uses a formalized setting of gaining opinions from experts to assist in developing probabilities for use in a wide variety of applications. Additional information for the use of EOE can be found in Ayyub, Blair, and Patev (2002).

### **3.3.2 Engineering design inadequacy (Hazard 1.1.1 a + b)**

This hazard is of a general nature because the character and location of the design inadequacies are generally not known. An error in the design stability calculations of a segment for various floating stages is one type of error that warrants highlighting separately.

The main source of information about the frequency of structural design inadequacies is project statistics. These statistics are not sufficiently extensive and explicit to allow a breakdown into specific error types.

The frequency of design errors (in general) that have had significant consequences is based on the marine construction project overview provided in Appendix C. Only a few projects (3 of 108) are directly comparable to the Braddock Dam project. This amount of data does not provide a statistically significant basis. The available project statistics from Appendix C are summarized in Table 3-3.



**Table 3-3**  
**Problems Experienced in Marine Projects Listed in Appendix C**  
**That Could Be Traced to Design Engineering Inadequacies**

Project Type	Number of Projects	Significant <sup>1</sup> or Catastrophic <sup>2</sup> Problem		Catastrophic <sup>2</sup> Problem	
		Number	Relative Frequency %	Number	Relative Frequency %
Offshore platforms	36	3	8	1	3
Floating vessels, bridges, docks	18	0	<6	0	<5
Locks and dams	3	1	33	0	<25
Immersed and floating tunnels	51	2	4	0	<2
All projects	108	6	5.6	1	0.93

<sup>1</sup> A significant problem corresponds to the Medium consequence category.  
<sup>2</sup> A catastrophic problem corresponds to the High consequence category.

The probability of significant or catastrophic problems due to design engineering inadequacies ranges from 4 to 33 percent. The high value of 33 percent is based on only three cases. The single common average is 5.6 percent. Hence, using the common average, approximately 1 out of 18 projects is exposed to a design inadequacy with severe consequences. The similar probabilities for catastrophic consequences range from <2 to <25 percent with a common average of 0.93 percent, representing 1 out of every 108 projects.

It is tempting to use the simple statistics for catastrophic problems associated with the project types "locks and dams" and "immersed and floating tunnels." However, the statistics of no situations occurring for a small sample does not imply that the probability can be concluded to be zero. A rough intuitive estimate of an upper bound on the probability could be based on the assumption that an imaginative "next project" in the population would have catastrophic consequences. In that case, the probability estimate for the two populations would be  $1/4 = 25$  percent and  $1/52 = 2$  percent, respectively. It is noted that, according to estimation theory, these values represent the 78 and 98 percent upper confidence limits, respectively, and represent upper bounds on the catastrophic consequences probability.

Considering the uncertainties inherent in risk analysis and the magnitude of the occurrence probabilities established for the other hazards, it is not significant whether the probability of a catastrophic problem due to design errors is 2, 3, 5, or even 25 percent. The risk contribution for a catastrophic design problem will typically be among the dominant risks, whichever value is used. The estimate based on all projects (0.93 percent) is used in the calculations in Appendix B.

The statistics given in Appendix C also provide the basis for estimating the occurrence frequency of engineering construction errors and construction contractor errors. The associated hazards are 3.1.1 a+b: *Construction engineering problem* and 3.1.1 c+d: *Construction contractor problem*. Determination of the occurrence probability for those follows the approach described above.

### 3.3.3 Collision to bridge pier during tow of segment (Hazard 3.7.3 b)

The probability of occurrence of this hazard has been analyzed using calculation models specified for risk analysis of ship impact to bridges as presented in Federal Highway Administration (FHWA) (1990). The model uses the size of the vessel (here the segment), the size of the navigational opening in the bridge, and the characteristics of the waterway in the vicinity of the bridge to calculate the probability of an impact. The probability of aberrancy (that the tow loses control) is based on statistics given in Whitney et al. (1996) for a flotilla or barge tow. The expected value for the aberrancy probability on the Ohio River is determined to be  $5.29 \times 10^{-4}$ . This value is significantly above the base rate of  $1.2 \times 10^{-4}$  suggested in FHWA (1990), and the higher value is adopted in the present assessment. The impact calculation is systematically made for each of the 20 bridges to be passed on the route, leading to a 0.57 percent probability of collision.

From the framework of the calculation model, it follows that the collisions for which the probability is calculated cover both minor and more severe collisions. A crude representation of this is introduced by assuming that 65 percent of the collisions are small (i.e., with minor damage as the result), 30 percent of the collisions are moderate with some damage, and only 5 percent of the collisions will be severe with catastrophic loss of segment consequences. This is based on engineering judgment.

### 3.3.4 Grounding of a segment during tow (Hazard 3.7.1 a)

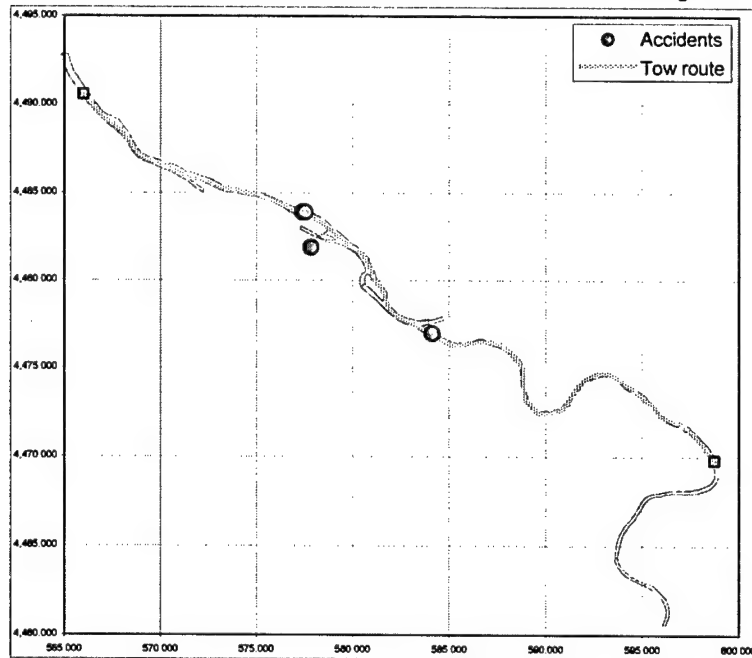
A source of information for the probability of grounding while a tow is passing a certain stretch of river is the navigational accident database published by the U.S. Coast Guard. For this example, data from 1996-97 have been used. These data are publicly available on the Internet, and the charts in Figure 3-2 show the accidents recorded along the tow route.

To derive a frequency of grounding per passage, the observed number of accidents has to be made relative to the number of tows that have passed along the route during the time interval considered. Hence, the traffic has to be known. The U.S. Army Corps of Engineers provides useful information for this purpose in terms of published lock passage statistics. This database is called the Lock Performance Monitoring System (LPMS) and is also publicly available on the Internet. Using the statistics from LPMS for 1996-97 on the number of barge tows that locked through the three locks along the route, about 13 tows pass through the locks per day. This becomes about 10,000 passages of the route for the period 1996-97. Four accidents similar to groundings were recorded. An estimate of the probability for an accident during one passage of the route thus becomes

$$\text{Probability estimate} \approx \frac{4}{10,000} = 0.04 \text{ percent}$$

Groundings, Collisions, Allisions, Loss of Control

4 accidents during 1996-97



All accidents

7 accidents during 1996-97

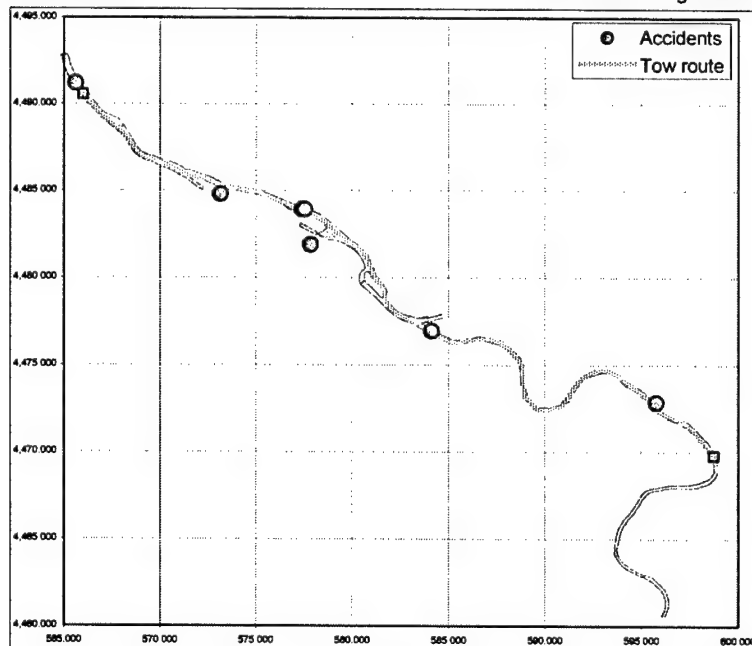


Figure 3-2. Locations of tow accidents along the planned tow route (as reported by the U.S. Coast Guard for 1996-97<sup>1</sup>)

<sup>1</sup> The mapping of the river contour is approximate. This explains that some accidents appear to be located on land.

A factor of 2 is applied because two segments are to be towed, and a reduction factor of 1/3 is introduced because the tow will be done in a “good time window,” most likely with the traffic on the river shut down during the tow. This brings the estimated probability of grounding down to 0.03 percent.

### **3.3.5 Contingency mooring failure at the outfitting pier during high river stage (Hazard 3.8.1 e)**

A single mooring point will be constructed upstream of the outfitting pier as a contingency in the event of a flood with a segment at the outfitting pier. The mooring point is designed for hydraulic forces corresponding to a 500-year return period flood. Overloading may occur if a more severe flood occurs while a segment is at the pier. The mooring system failure load is conservatively assumed as twice the design load for calculating the occurrence probability. A larger capacity demand ratio is typical.

The river hydrology statistics at the outfitting pier, as defined in the project Design Memorandum, are used to calculate the probability of exceeding twice the design load. The drag force on the segment is assumed to be proportional to the square of the river velocity, so exceeding twice the design load is equal to the river velocity exceeding 1.41 times the design velocity. The return period of a river velocity equal to or larger than this value is estimated to be  $2 \times 10^9$  year.<sup>1</sup> Each segment will be located at the outfitting pier for a 3-month period; thus, the probability of exceeding the contingency mooring system capacity while one of the two segments is at the outfitting pier becomes

$$2 \times \frac{0.25 \text{ year}}{2 \times 10^9 \text{ year}} = 2.5 \times 10^{-10}$$

This occurrence probability can be considered negligible. However, this estimate covers only structural failure of the mooring system. It does not include the possibility of inadequate design or construction of the mooring or attachment to the mooring point. Due to the very small probability of structural failure, human errors in relation to fabrication and mounting are likely to be governing in this case. This is covered in the general hazards dealing with design or construction inadequacies. (See Section 3.3.2.)

### **3.3.6 Segment floats over the outfitting pier during high water and is damaged when the river stage drops (Hazard 3.8.1 f)**

An extended fender system is installed to prevent a segment from floating over the outfitting pier during a flood. The extended fender is designed for a flood with a 500-year return period. The fender will, if properly designed, be able to function at a very high probability, ensuring that the *reliability* of the fender will be close to 100 percent. The fender system reliability reduces as the river

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<sup>1</sup> Available statistical data do not explicitly cover such infrequent situations, and theoretical approximations have been extrapolated to provide this return period.

stage rises above the 500-year recurrence stage. When the river stage is 10 ft (3 m) above the 500-year level, a segment bottom will be clear of the fender system and the reliability of the fender system will be 0 percent. It is assumed for this study that the reliability varies linearly from 100 percent at the design river stage to 0 percent at 10 ft (3 m) above. Integration of this variation with the probability density function of the flood level leads to an occurrence probability estimate of segment float-over of approximately  $1.8 \times 10^{-4}$ . Thus, this hazard has a higher occurrence probability than the contingency mooring failure.

The probability of a segment finally resting on top of the outfitting pier will not occur before the river stage drops again, and only if the segment remains in a lateral position over the outfitting pier. This offers opportunities for intervention or hydraulic velocity toward midstream to prevent a situation from developing that would have serious consequences. This is represented in the event tree shown in Figure 3-3.

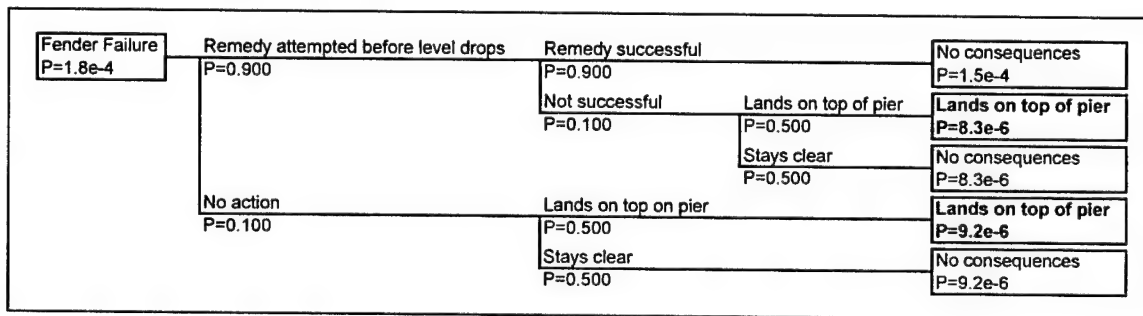


Figure 3-3. Event tree describing possible scenarios for segment overtopping of the outfitting during a flood

The event tree branching probabilities are based on engineering judgment. This will often be the case, since more substantiated statistical values are not available. By making allowance for intervention and change, the probability that a segment lands on top of the pier is estimated at  $9.2 \times 10^{-6} + 8.3 \times 10^{-6} = 1.76 \times 10^{-5}$  or 0.00176 percent.

### 3.4 Consequence Evaluation

The primary types of consequence in a construction risk analysis are damage to the construction works and delay of the project. Depending on the project, it may be relevant also to consider the risk of human injury and the risk of environmental damage. For the present project, however, these are not considered relevant.

The direct consequences of a hazard will typically be damage to or loss of parts from the project structures. The cost and time required to reestablish the damaged or lost structures is used as the quantifiable consequences. In the present study the contractor's schedule and cost breakdown have been made available so that evaluation of cost and delay can be done with direct reference to the resource requirement for the planned construction works. Many of the

hazards included in the hazard master list may result in damage to or loss of one of the floating segments. For simplicity, the associated cost and delay are assumed equal to the accumulated resources invested in the segment at the time of the damage or loss. The accumulated cost of the segments at various stages of the project (launching, tow to outfitting, outfitting, tow to site, setdown) is provided in Appendix D. The costs used in the example reflect only the replacement costs based on Appendix D and do not reflect any cost-plus contingencies or costs due to delays to the contractor or possible delays to navigation.

Evaluation of the extent of damage is based primarily on engineering judgment and includes, whenever relevant, a trival estimate (minimum, likely, maximum) to indicate the range of variation. For example, engineering judgment is the basis for the damage-level occurrence probabilities and segment/pier cost estimates when quantifying the Hazard 3.7.3.b consequences of a segment impacting a bridge pier. Estimated values based on engineering judgment for the hazards included in this study are referenced on individual risk analysis worksheets in Appendix B.

### 3.5 Risk Evaluation and Summary

Many different approaches are encountered in the compilation and presentation of the “total risk picture” or “risk profile” of the project. The simplest, and least informative approach is to calculate the average risk: the sum of the products of frequency (or probability) and consequence estimate for each hazard. A hazard with an occurrence frequency of 0.01 percent per project and an associated cost of \$100,000 per occurrence will contribute by

$$0.0001 \frac{\text{Occurrence}}{\text{Project}} \times \frac{\$100,000}{\text{Occurrence}} = \$10 \text{ per project}$$

An average cost of \$10 per project from the hazard does not warrant much concern. However, the actual cost associated with the hazard (\$100,000) if it happens is more likely to attract attention to the hazard, and a larger effort is made to ensure that the expected occurrence frequency is as low as stated.

The average cost associated with the hazards analyzed in Appendix B ranges from \$129,000 to \$355,000 depending on whether the low or high cost estimates are used in the calculation.

A similar but more definitive approach is to establish the distribution function of the accumulated cost and delay for the project on the basis of the identified and quantified hazards. The representation obtained provides a more useful picture because the full range of project cost and delay is presented, including the highly unlikely situations. Such a combination is illustrated in Figure 3-4 for the seven hazards for which quantitative analysis has been performed. The horizontal axis of the diagram gives the total additional cost *due to the hazards* for the project. The vertical axis gives the exceedance probability.

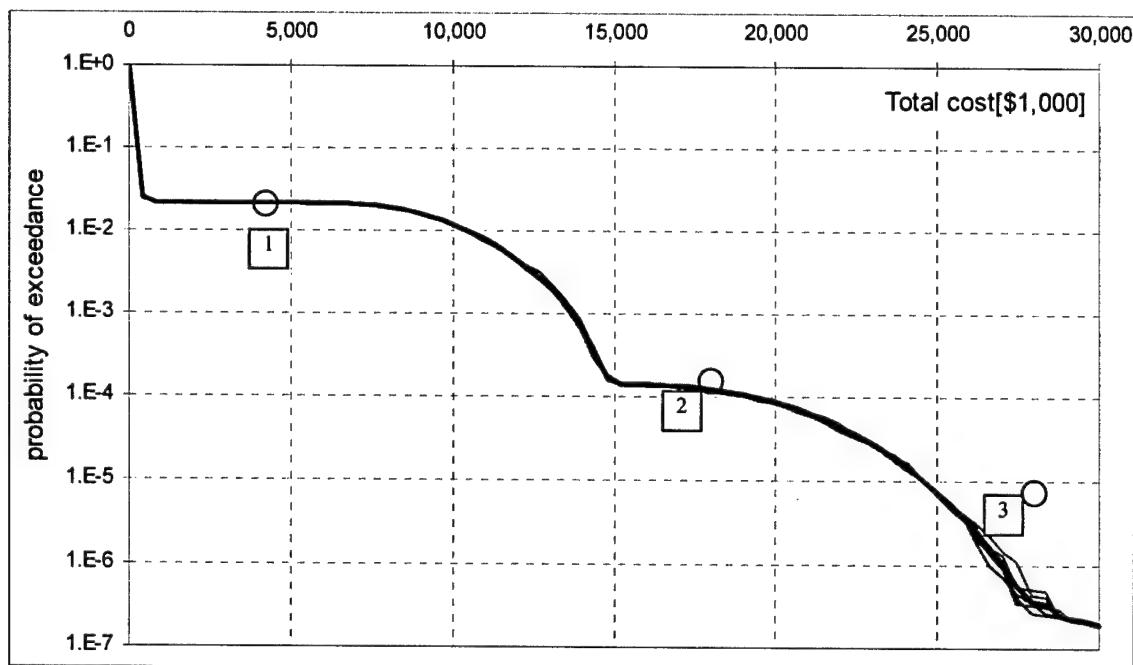


Figure 3-4. Combined risk profile for the hazards selected for quantitative analysis (five simulated curves and the average of those)

Interpretation of the diagram is explained in terms of the three points on the curve:

**Point 1:** The total hazard cost exceeds \$1 million with a probability of 2.2 percent.

**Point 2:** The total hazard cost exceeds \$15 million with a probability of 0.015 percent.

**Point 3:** The total hazard cost exceeds \$25 million with a probability of 0.00076 percent.

The presentation provides a direct and useful input to the decisions on insurance coverage for the project. The above curve suggests that the coverage of the insurance should be on \$15 million to reduce the risk significantly. A drawback of the above presentation is that points on the curve cannot be traced to a specific hazard.

This type of trade-off analysis is termed multiple-criteria decision-making and can be used to minimize both risks and costs and find an optimal solution. Reference is made to Lambert et al. (2001) and Tsang, Lambert, and Patev (2002) for further information.

The most versatile graphical representation of the risk analysis is the scatter diagram shown in Figure 3-5. The diagram shows the various contributions to the risk assessment as points in a chart, with consequences along the horizontal axis and frequency of occurrence (or probability) along the vertical axis. Points

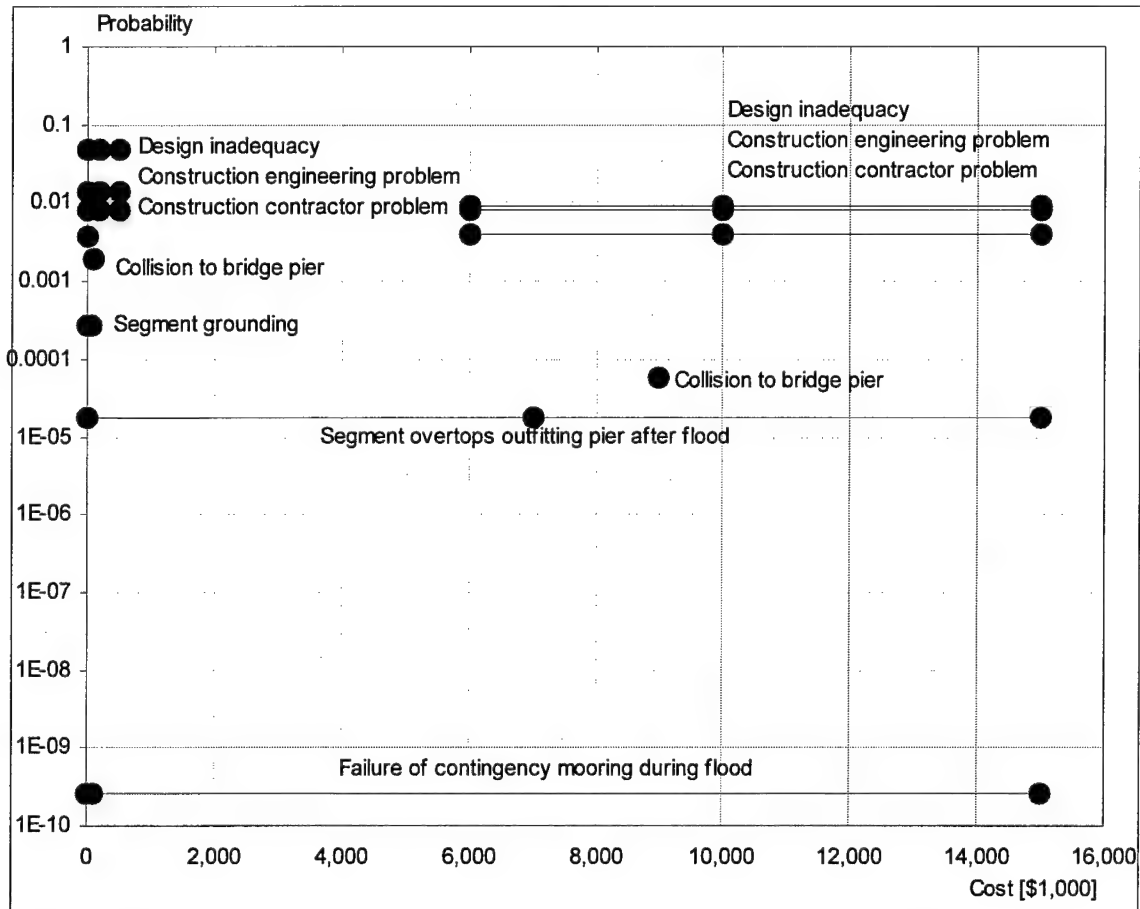


Figure 3-5. Scatter diagram for cost associated with the hazards selected for quantitative analysis

in the lower left corner of diagram represent negligible risk contributions (low frequency and small consequences), and points toward the upper right corner represent large risk contributions (high frequency and large consequences). The points are connected with a line when a range of consequences is specified for the same occurrence frequency.

From the scatter diagram it is evident that the primary hazard is design errors that may result in loss of one segment during the marine operations. Second comes the risk from collision to bridge piers during the tow and the possibility that the segment might end on top of the outfitting pier after a flood. However, the occurrence frequency of these contributions is more than 1,000 times smaller than the dominating contribution from design errors.

The scatter diagram presents the relative contributions from the various hazards and *cannot* be used to make conclusions on the total or accumulated risk on the project as a whole. The accumulated measures previously presented, the average risk and the risk profile, can be used for such assessments.



## 4.0 Risk Mitigation Recommendations

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The key parameters of events and hazards determining critical project risk have been identified for the hazards selected for analysis on Braddock Dam. Feasible mitigation recommendations are proposed if possible. These recommended mitigation measures or plans are summarized in the following list:

- a.* Detailed review of construction transportation procedures and plans, including planned contingencies.
- b.* Independent technical review of construction engineering stability evaluations and calculations for both segments for all postulated configurations.
- c.* Independent technical review of engineering design criteria calculations for possible design omissions typical of thin shell design of both segments for all postulated configurations.
- d.* Detailed review of segment stability and control during setdown, including external hazard source.

Hazard identification, hazard screening, and risk quantitative analyses should be completed for all Braddock Dam hazard list items to complete the risk assessment of the current planned activities. Risk mitigation recommendations become more specific as the details of the complete assessment become available.

The Braddock Dam project comprises several examples of risk mitigation activities. Specific attention has been directed to the innovative construction activities. Several detailed mitigation measures have been incorporated in the Braddock Dam construction plans as a result of informal risk evaluations. These detailed mitigation activities include but are not limited to the following:

- a.* Detailed "Instructions to Field Engineering" documents.
- b.* Testing (by the U.S. Army Engineer Research and Development Center, Vicksburg) of segment transits from outfitting to damsite with detailed positioning recommendations.

- c.* Prototype segment transportation run-throughs.
- d.* Restriction of river traffic during segment transport.
- e.* Design and construction of a flood anchor pile at the outfitting pier.
- f.* Design and construction of outfitting pier fenders for 500-year flood.
- g.* Extensive segment positioning methods to ensure that setdown tolerances are met.
- h.* Tremie concrete trial pours for drilled piles.

If formal risk assessment methods are to be effective for mitigating possible risks of innovative construction techniques, risk evaluations should incorporate the hazard identification, hazard screening, and risk quantitative analyses of these revised design and construction conditions.

## 5.0 Historical Marine Construction Problems and Failures

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A summary of marine construction problems and failures that have been encountered on concrete marine projects using innovative construction methods has been compiled. These problems and failure events are listed and described in Appendix C, along with data regarding the perceived cause. The data are categorized as to design engineering, construction engineering, and contractor issues, with their associated occurrence probabilities. A summary of the historical marine floating construction data identifies the following general problems areas:

- a.* Unit/segment stability problems.
- b.* Unforeseen design change problems.
- c.* Environmentally caused problems.

The detailed calculations required to determine occurrence probabilities for various categories are also provided in Appendix C. The occurrence probabilities derived on this basis are used to establish the risk of more generic hazard types, and this provides an independent reference for the risks calculated for the more specific hazards.

## 6.0 Conclusions and Recommendations

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### 6.1 Conclusions

The example risk assessment performed in this study illustrates the approach to use and shows some important characteristics of the hazards to be considered in such a study. When scrutinizing a carefully planned construction project such as Braddock Dam, it is found that many of the specific hazards in the project had been identified and contingency mitigation measures introduced as appropriate.

If it is assumed that the project is carried out according to the final proposed construction plans, the risk level is relatively low. Experience demonstrates that significant problems have occurred during innovative marine-type projects and, in many cases, those problems have been attributed to construction contractor mistakes; construction engineering revisions, changes, omissions, or insufficient consideration of extreme environmental conditions; and engineering design inadequacies in structural calculations or stability calculations. The environmental hazard (river flooding) has been thoroughly addressed in the sample project and does not appear to present a significant risk. Construction contractor mistakes or construction engineering calculation inadequacies remain as the dominating hazards, based on the hazards selected for quantified analysis. The occurrence probabilities and consequences for these hazards are estimated using the general historical database developed in Appendix C. Historically, the setdown process is shown to be an exposed phase, and the problems can have high loss consequence potential. This is reflected in the high risk associated with Hazards 1.1.1 *a-b* and 3.1.1 *a-d*.

Priority mitigation and contingency activities include thorough surveillance of the construction works and quality assurance of the construction engineering design. These activities include design reviews, independent checks, and field condition verification. In summary, risk assessments determine the activities that have the highest risk against project completion and require the greatest effort toward mitigation and thus ensure the highest probability of a successful construction project.

## 6.2 Recommendations

The critical events or hazards with relatively high occurrence probabilities or high consequence damage and cost potential were selected on the basis of engineering judgment and the availability of statistical data. The following recommendations are offered:

- a.* A formalized risk assessment program should be developed and incorporated in major lock and dam construction projects. The initial program should be integrated with the independent technical review program.
- b.* A formal risk assessment guideline should be developed.
- c.* Risk analysis technical aids should be provided (similar to the Failure Mode and Effects program). These would include methodology techniques, master list formats, screening guidelines, and occurrence probability databases.
- d.* Statistical data should be formalized and published for assessment use. These include items such as towboat loss of power frequency; runaway barge size, velocity, and associated frequency; generic statistical distribution functions for structural capacity calculations; and generic statistical data for barge impact criteria and calculations.
- e.* Information about inadequacies in design and significant noncompliance of the construction work should be collected to provide an improved statistical basis for determining the occurrence frequency of important root causes.
- f.* Risk mitigation measures should be taken and addressed in a tabular format for documentation purposes. This approach creates an entire decision chain regarding mitigation measures that were considered during the innovative project.

## 7.0 References

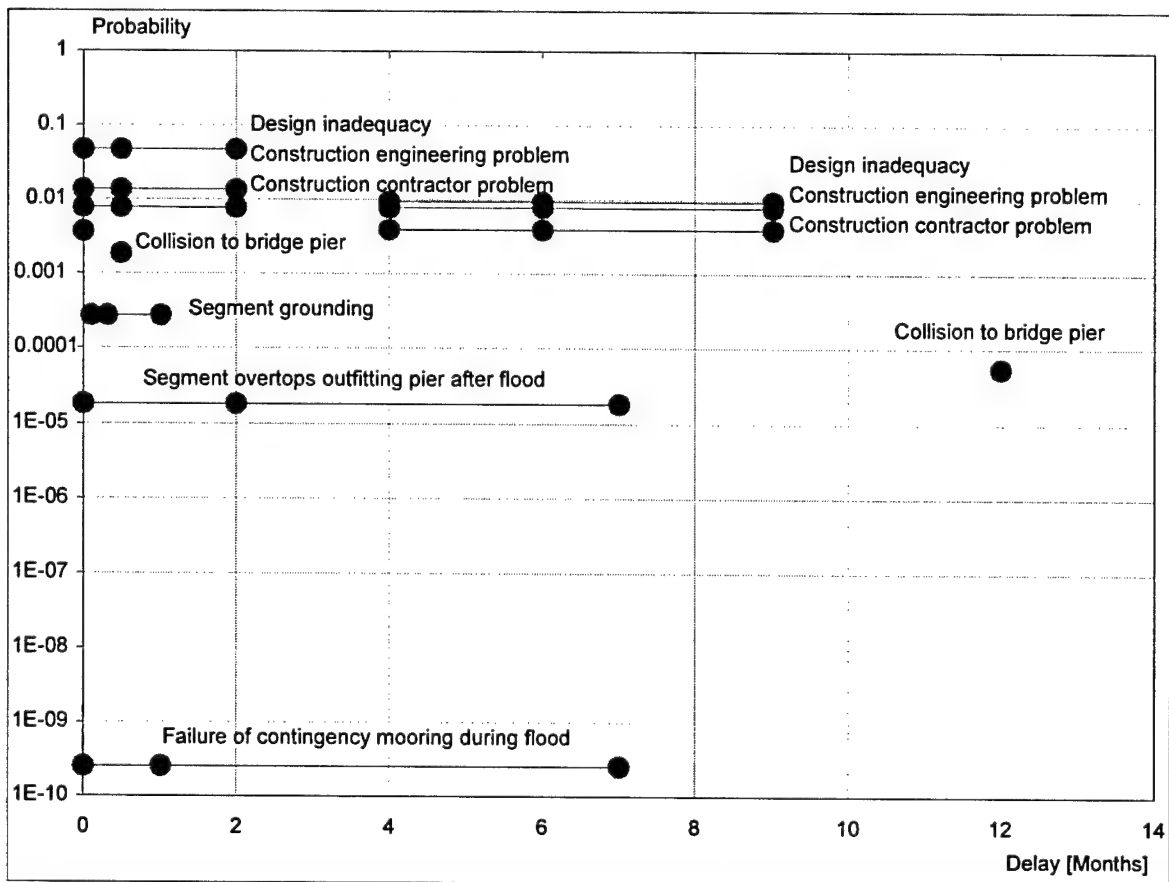
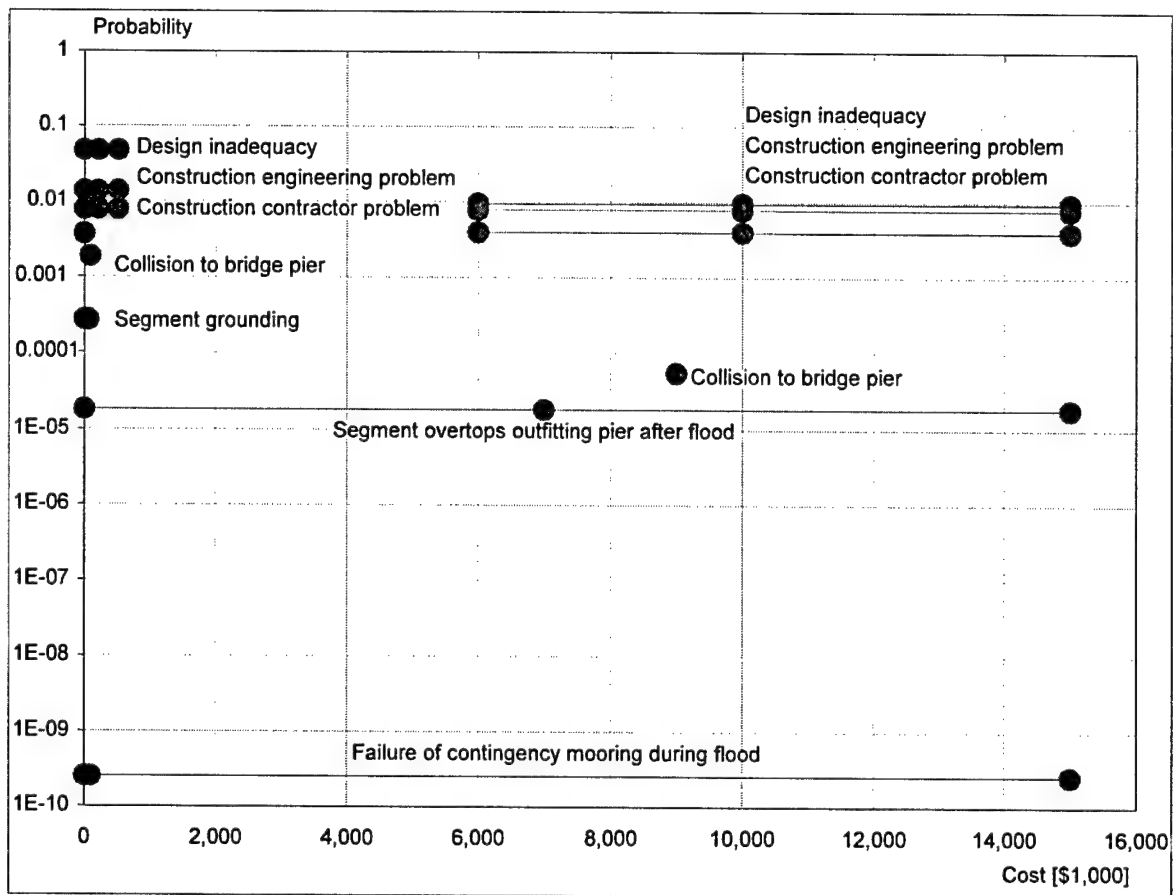
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# **Appendix A**

## **Hazard Identification and Risk Analysis Master List**

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# Hazard Identification and Risk Assessment

Hazard Identification and Risk Assessment													
Activity		Hazard		Occurrence [per project]	Fatalities			Cost [\$1,000]			Delay (months)		
					Low	Medium	High	Low	Medium	High	Low	Medium	High
1	Preconstruction												
1.1.1	Design		a. Design inadequacy causing significant problems to the floating segments b. Design inadequacies causing catastrophic problem (loss) to the floating segments  Errors in bid documents or procedures Inexperienced contractor is selected	0.0467  0.0093	0  0	0  0	0  0	10  6000	200  10000	500  15000	0  4	0.5  6	2  9
1.1.2	Bid												
1.1.3	Award of contract												
2	Initial Planning, Procurement, and Preparations												
3	Prefabrication of Dam Segments												
3.1.1	General construction		a. Construction engineering problem with significant consequences b. Construction engineering problem with catastrophic consequences c. Construction contractor problem with significant consequences d. Construction contractor problem with catastrophic consequences	0.014 0.008 0.008 0.004	0 0 0 0	0 0 0 0	0 0 0 0	10 6000 10 6000	200 10000 200 10000	500 15000 500 15000	0 4 0 4	0.5 6 0.5 6	2 9 2 9
3.2	Provision and development of precasting site												
3.2.1	Permits		a. Permit for dredging basin and river wall closure not available b. Environmental permits - runoff water treatment pending, etc. c. Excavated site material environmentally polluted b. Archeological finds; halts further development of the site until the finds have been explored c. Permeable soil layers allow large/uncontrolled inflow to the basin d. Excessive riverbank erosion around sheet piles lining the channel - e.g. during a spring flood e. Site excavation severs underground utilities f. Site flooded due to high river stage criteria exceedance (10-year storm)										
3.2.3	Batch plant		a. Uncertified batch plant (CMAA certs or equivalent) b. Scales not calibrated c. Moisture content of aggregate not controlled c. Inadequate aggregate gradation (out of spec) d. Trial mix test cylinders have low breaks e. Cement and admixture - certs not available/out of spec - storage unacceptable f. Obtaining approval of aggregates a. Inadequate/unspecified soil compaction under grade beams, berms, roads, etc. b. Grade beam uncontrolled settlement c. Unstable basin berms and slopes d. Instability in slopes between upper and lower basin interface										
3.2.4	Basin design		a. Low production concrete test cylinder breaks b. Rebar congestion and interference; design change required c. Inadequate steam curing facilities d. Lightweight concrete mix revisions due to strength, slump, workability e. Panel failures during lifting f. Late discovery of nonconformance requiring recasting										
3.3	Precasting of elements												
3.3.1	Production		a. Joint rebar out of alignment and does not allow correct erection of the elements b. Excessive wind loading on panels prior to pouring c. Inappropriate placement procedures create voids under walls a. Splitting of the slab during post-tensioning due to inadequate control with expansion agent or insufficient confinement b. Plugged ducts Rock pocket at maximum shear plane Brace end connection failure (embed pullout) a. Rock pockets at connections to precast panels b. Macro cracking of concrete rendering rebar corrosion protection inadequate										
3.4	Production of segment (both segments)												
3.4.1	Erection of precast elements												
3.4.2	Casting of base slab												
3.4.3	Post-tensioning of base slab												
3.4.4	Concreting connections (closure pours)												
3.4.5	Install temporary bracing inside shells												
3.4.6	Form and cast top slabs												
3.4.7	Place ballast concrete												
3.4.8	Install equipment and temporary structures for towing												
3.5	Flooding and launching, Segment 1												
3.5.1	Flood basin to max level (+15 ft)		a. Segment does not separate from base grade beam (sufficient pressure does not develop under segment) b. Uneven lift-off from base causing overstress (bending stress) of the segment										

Hazard Identification and Risk Assessment												
Activity		Hazard		Occurrence [per project]		Fatalities		Cost (\$1,000)		Delay [months]		
				Low	Medium	High	Low	Medium	High	Low	Medium	High
3.5.2	Move Segment 1 to deep basin	c. Unrecognized permeable layers or buried drains/pipes above river stage causing failure of temporary sheet pile cutoff wall at river to basin interface	d. Failure of river cutoff wall/dike when water pressure is reversed									
3.5.3	Lower basin water level to river stage	e. Unacceptable leakage into floating segment	a. Heavy rainfall or leakage into segment increasing draft and risk of grounding									
3.5.4	Open channel to launch Segment 1	b. Insufficient winching capacity to move Segment 1 from upper to lower basin	Instability of the saturated basin slopes when water level is lowered causing severe mudslides and slope failures									
3.5.5	Close channel	Lower basin river access channel depth and width insufficient for segment to exit basin into Ohio River	Excessive basin berm and sheet-pile wall displacement causing channel width into river to become too narrow for Segment 2									
3.5.6	Dewater basin	Excessive groundwater intrusion causing inability to maintain low-water stage in lower basin	Berm and/or cutoff wall has become weak due to opening and reclosure causing failure during upper basin flooding									
3.6	Flooding and launching, Segment 2	Heavy rainfall or leakage into segment increasing draft and risk of grounding										
3.6.1	Flood basin to max level (+15 ft)											
3.6.2	Move Segment 2 to deep basin											
3.6.3	Lower basin water level to river stage											
3.6.4	Open channel to launch Segment 2											
3.7	Transport to outfitting (both segments)											
3.7.1	Towing on open river											
3.7.2	Passage of lock (3 locks)											
3.7.3	Passage of bridges (19 bridges)											
3.7.4	Mooring at outfitting pier											
3.8	Outfitting (both segments)											
3.8.1	General											
3.8.2	Extending piers											
3.8.3	Casting of sill crest											
3.8.4	Height extension of downstream temporary bulkheads											
3.8.5	Install temporary upstream bulkhead											
3.8.6	Installation of equipment											
3.8.7	Complete ballasting											
3.8.8	Install underbase grout piping											
3.9	Transport to site (both segments)											
3.9.1	Release mooring											
3.9.2	Rotate segment											
3.9.3	Passage of bridges (2 bridges)											
3.9.4	Turn segment into dam pool											
4	Maintenance Bulkheads											
4.1	Prefabrication of maintenance bulkheads											
4.1.1	Transport to site											
4.1.2												

# Hazard Identification and Risk Assessment

Activity	Hazard	Occurrence [per project]			Fatalities			Cost (\$1,000)			Delay [months]		
		Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
5	Tainter Gates												
5.1.1	Fabrication												
5.1.2	Delivery to site												
	Foundering/loss of transport												
5.1.3	Assemble gate components on barge												
	a. Pad/component is lost during assembly												
	b. Collision by passing craft												
6	Dam Site Activities												
6.1	Site preparation												
6.1.1	General												
6.1.2	Installation of cutoff walls												
6.1.3	Dredging												
6.1.4	Preparation of gravel base												
6.1.5	Installation of H-piles												
6.1.6	Installation of drilled shafts												
	a. Inaccurate positioning of drilled shaft												
	b. Insufficient quality - or uncertainty about quality - of tremie concreting												
	c. Damage to steel casing by overpassing vessel before concreting has been completed												
	d. Damage to shear pin by overpassing vessel, dropped object, etc.												
	e. Flooding of casing during completion in the dry of the shaft top												
	f. Inaccurate cutoff elevation												
6.2	Positioning and setdown, Segment 1												
6.2.1	General												
	a. Failure of pipes/valves in ballasting system												
	b. Failure of bulkhead(s)												
6.2.2	Position over dam axis aligned parallel to current												
6.2.3	Run mooring lines												
	Mooring lines gets entangled in drilled shafts												
6.2.4	Start rotation												
6.2.5	Tension mooring and release of main lug												
	a. Failure of mooring points/piles/lines												
	b. Equipment is dropped in water within the segment footprint, has to be recovered												
6.2.6	Rotate and align												
6.2.7	Ballast to 6 in. above final grade												
6.2.8	Final horizontal adjustment with hydraulic rams												
	Failure to control stability during ballasting												
	a. Failure of hydraulic ram system												
	b. Failure of contact points												
	a. Failure in flat jack system (loss of pressure)												
	b. Fouling of grouting pipes												
6.2.9	Set down on 6 drilled shafts, level with flat jacks and lock (grout) jacks												
	a. River traffic (barge or towboat) collides with segment (usual river stage)												
	c. Failure in ballasting system/procedure leading to overloading of setdown shafts												
6.2.10	Flood bays partially to ensure 10-20% submerged weight												
6.3	Positioning and setdown, Segment 2												
6.3.1	General												
	a. Failure of pipes/valves in ballasting system												
	b. Failure of bulkhead(s)												
6.3.2	Position 300-400 ft upstream from dam axis aligned parallel to current												
6.3.3	Run mooring lines												
	Mooring lines gets entangled in drilled shafts/piles												
6.3.4	Start rotation												
6.3.5	Tension mooring and release of main lug												
6.3.6	Rotate segment transverse to current												
6.3.7	Translate to position above dam axis and align												
	a. Failure of anchor or mooring point												
	b. Impact to Segment 1												
	c. Failure of horn guide												
6.3.8	Ballast to 6 in. above final grade												
	a. Failure to control stability during ballasting												
	b. Failure of end wall support												
6.3.9	Final horizontal adjustment with hydraulic rams												
	a. Failure of hydraulic ram system												
	b. Failure of contact points												
6.3.10	Set down on 6 drilled shafts and level with flat jacks, lock (grout) jacks												
	a. Failure in flat jack system (loss of pressure)												
	b. Fouling of grouting pipes												
	c. River traffic (barge or towboat) collides with segment (usual river stage)												
	Failure in ballasting system/procedure leading to overloading of setdown shafts												
6.3.11	Flood bays partially to ensure 10-20% submerged weight												
6.4	Grouting and infill, Segment 1												
6.4.1	General												
6.4.2	Underbase grouting												
	a. Compartment blowout due to large head in vertical ballasting/grouting pipes												
	b. Grout bags do not provide full sealing												

Hazard Identification and Risk Assessment									
Activity	Hazard	Occurrence (per project)	Low	Medium	High	Low	Medium	High	Delay (months) Low Medium High
8.4.3 Tremie infill of segment compartments	b. Incomplete filling - voids								
8.4.4 Drilled shaft top grouting (remove jacks from setdown shafts)	Incomplete filling - voids								
8.4.5 Dewater bay 1	Failure of bulkheads								
8.4.6 Place remaining infill concrete in bay 1 in the dry	a. Incomplete filling - voids b. Hydration heat or temperature gradient is too large and causes cracks in upper surface (corrosion problem)								
8.4.7 Dewater bay 2	Failure of bulkheads								
8.4.8 Place remaining infill concrete in bay 2 in the dry	a. Incomplete filling - voids b. Hydration heat or temperature gradient is too large and causes cracks in upper surface (corrosion problem)								
8.4.9 Dewater bay 3	Failure of bulkheads								
8.4.10 Place remaining infill concrete in bay 3 in the dry	a. Incomplete filling b. Overfilling - temperature problems								
8.5 Grouting and infill, Segment 2									
8.5.1 General	Compartment blowout due to large head in vertical ballasting/grouting pipes								
8.5.2 Underbase grouting	a. Grout bags do not provide full sealing b. Incomplete filling								
8.5.3 Tremie infill of segment compartments	Incomplete filling - voids								
8.5.4 Drilled shaft top grouting (remove jacks from setdown shafts)	Failure of bulkheads								
8.5.5 Dewater bay 4	a. Incomplete filling - voids b. Hydration heat or temperature gradient is too large and causes cracks in upper surface (corrosion problem)								
8.5.6 Place remaining infill concrete in bay 4 in the dry	Failure of bulkheads								
8.5.7 Dewater bay 5	a. Incomplete filling - voids b. Hydration heat or temperature gradient is too large and causes cracks in upper surface (corrosion problem)								
8.5.8 Place remaining infill concrete in bay 5 in the dry									
8.6 Grout and post-tension segment joint									
8.6.1 Grout joint using tremie technique	a. Incomplete sealing by grout bags/pipes b. Incomplete filling - voids Failure of bulkheads								
8.6.2 Dewater bays and post-tension segment joint									
8.7 Construction of piers									
8.7.1 Erection of precast panel shells (and trunnion post-tensioning bars)	Drop of element								
8.7.2 Cast infill concrete	Element is dropped/damaged								
8.7.3 Install trunnion girders	a. Failure of embedded post-tensioning rods (overloading) b. Fracture of trunnion girder c. Delamination of concrete								
8.7.4 Post-tension trunnion girders									
8.8 Installation of fairlance									
8.8.1 Positioning of precast elements									
8.8.2 Tremie void under elements									
8.9 Install gate machinery (all bays)									
8.10 Complete electrical and mechanical	Machinery is dropped in water								
8.11 Installation of fairlance gates (all bays)									
8.11.1 Float gate in by barge	a. Instability of barge - foundering b. Damage of gate due to impact during float-in c. Impact and damage to seal girders								
8.11.2 Mount the fairlance gate	Unwanted deformation of gate during erection (unsymmetric hoisting)								
8.11.21 Mount gate arms on trunnions	Failure of hydraulic system								
8.11.22 Lift gate off barge with hydraulic	Unbalance of hydraulic system - unsymmetric loading on gate Collision to sealing arrangements in bay								
8.11.23 Float out the barge	Collision to sealing arrangements on gate								
8.11.3 Dewater and finalize seal arrangement	Failure of bulkheads								
8.11.31 Install temporary bulkheads and dewater bay	Insufficient filling								
8.11.32 Adjust steel seal arrangements and make closure pours	Water entrance and scour/washout of closure pours								
8.11.33 Flood the bay									
8.12 Construction of left closure weir	Flood situation before weir is closed, damage to structures								

Hazard Identification and Risk Assessment														
Activity		Hazard	Occurrence [per project]			Fatalities			Cost [\$1,000]			Delay [months]		
			Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
6.12.1	Driving sheet piles	Damage to sheet piles												
6.12.2	Fill cells with granular material													
6.12.3	Pour concrete cap													
7	Demolition of Existing Dam													
7.1.1	Make 5-ft-wide hole in existing dam	Stability problems												
7.1.2	Allow water level in pool to fall slowly													
7.1.3	Monitor stability of new dam, lock river wall, and left abutment													
7.1.4	Continue demolition													
7.1.5	Install weep holes and rock anchors in left abutment													
8	Restoration of Site(s)													

# **Appendix B**

## **Risk Analysis Worksheets**

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# Braddock Dam Risk Assessment

## Hazard Analysis Calculations

Activity/(ies): 1.1.1 Design

Prepared HGL

Hazard: a+b. Design inadequacy causing significant or catastrophic problems to floating segment

Date 6/5/01

### Statistics on Engineering Design Errors:

**Table 1** Frequencies of engineering design problems on projects with significant or catastrophic consequences.

Project type	Total Projects	Eng. problem	Frequency
Offshore platforms	36	3	8%
Floating vessels, bridges, docks	18	0	<6%
Locks and dams	3	1	33%
Immersed and floating tunnels	51	2	4%
All projects	108	6	5.6%

**Table 2** Frequencies of engineering design problems on projects with catastrophic consequences.

Project type	Total Projects	Eng. problem	Frequency
Offshore platforms	36	1	3%
Floating vessels, bridges, docks	18	0	<6%
Locks and dams	3	0	<33%
Immersed and floating tunnels	51	0	<2%
All projects	108	1	0.93%

### Occurrence probability

Design error causing a significant problem in construction (5.6%-0.93%)= 4.7%

Design error causing catastrophic problem (loss) in construction 0.9%

### Consequences

Significant problem

	Cost [\$1,000]	Delay [months]
Low	10	0.0
Medium	200	0.5
High	500	2.0

Catastrophic problem (loss) (~100% of segment value)

	Cost [\$1,000]	Delay [months]
Low	6,000	4
Medium	10,000	6
High	15,000	9

### Significant problem

Frequency	Fatalities	Cost	Delay
4.7%	0	10	0
	0	200	0.5
	0	500	2

### Catastrophic problem

Frequency	Fatalities	Cost	Delay
0.93%	0	6,000	4
	0	10,000	6
	0	15,000	9



## Braddock Dam Risk Assessment

### Hazard Analysis Documentation

Activity/(ies): 1.1.1 Design

Prepared HGL

Hazard: a+b. Design inadequacy causing significant or catastrophic problems to floating segment

Date 6/5/01

Reference: Statistics of historic projects – presented within the Braddock Dam risk analysis.

Methodology: The occurrences of engineering design errors that cause significant problems during the construction are treated as one hazard that covers the entire project. The occurrence probability is based on statistics on similar concrete projects using float-in installation technique (offshore platforms, floating vessels, floating bridges, docks and piers, foundation caissons, submerged tunnels, locks and dams). Definition of engineering design errors as a hazard is based on design problems that may expose the project to complete loss of the structure or parts thereof, and this is also the basis of the referenced statistics. The statistics are applied directly to present project to determine the probability of engineering design errors, and consequences are assessed in terms of loss of one or both of the Braddock Dam segments.

Assumptions: Identification of specific engineering design errors that would present a hazard in the floating state (launching, tow, outfitting, positioning and setdown) is not attempted. Elimination of such errors is an integral part of the design process. It is not realistic to assume a more successful design review and error detection could be made in the framework of the risk analysis. The risk analysis thus assumes that all possible precautions have been taken to capture engineering design errors (i.e., selection of sufficiently qualified design team, performance of independent checks and design reviews, avoiding significant design changes late in the design process or—if such changes are necessary—provide the necessary resources for a thorough revision of the project).

Occurrence: Various categories of structures are considered in the historic project statistics, and some may appear more similar to the Braddock Dam project. However, to avoid subjective bias on the utilization of the statistics, the compound number for all project types is adopted. The probability of engineering design errors that will present a significant or catastrophic hazard to the project is thus 5.6%. In one fifth of those situations (corresponding to an absolute probability of 0.93%), complete loss of the structure (here, the segments) may result.

The probability estimates are very uncertain and display a significant variation between the different project types. Immersed and floating tunnels presents the most favorable numbers with only 4% probability for errors leading to a problem and less than 2% (no occurrences in 51 projects) probability for errors with catastrophic consequences. However, variability of the probability of occurrence by a factor of 2 to 3 will not be a concern in a construction risk analysis.

Consequences: Loss of both segments is not considered relevant because of the sequential project schedule. If significant problems arise with the first segment, the second segment can be changed to avoid the same problem before it reaches the stage where the problem emerged on the first segment. If the first segment is safely installed, only the second can be lost or severely damaged.

With reference to the statistical basis, the consequences of a “Significant problem” are judged as follows:

- **Cost:** equivalent to 5% of the value (construction investment) of one segment at the time of setdown
- **Delay:** 1-month delay

and the consequences of a “Catastrophic problem” are judged as follows:

- **Cost:** ranging between the value (construction investment) of one segment at launch and setdown, respectively
- **Delay:** 6-month delay

The above are considered likely consequences. A suitable range around the likely values has been judged to indicate the expected uncertainty.



# Braddock Dam Risk Assessment

## Hazard Analysis Calculations

Activity/(ies): 3.1.1 General Construction

Prepared HGL

Hazard: a+b. Construction Engineering problem

Date 6/5/01

### Statistics on engineering construction problems:

**Table 3** Frequencies of construction engineering problems on projects with significant or catastrophic consequences.

Project type	Segments Installed	Eng. problem	Frequency
Offshore platforms	44	5	11%
Floating vessels, bridges, docks	107	0	<1%
Locks and dams	8	1	13%
Immersed and floating tunnels	365	0	<0.3%
All projects	524	6	1.1%

**Table 4** Frequencies of construction engineering problems on projects with catastrophic consequences.

Project type	Segments Installed	Eng. problem	Frequency
Offshore platforms	44	2	5%
Floating vessels, bridges, docks	107	0	<1%
Locks and dams	8	0	<13%
Immersed and floating tunnels	365	0	<0.3%
All projects	524	2	0.4%

### Occurrence probability (for two segments)

Design error causing a significant problem in construction

1.4%

Design error causing catastrophic problem in construction (loss)

0.8%

### Consequences

Significant problem

	Cost [\$1,000]	Delay [months]
Low	10	0.0
Medium	200	0.5
High	500	2.0

Catastrophic problem (loss) (~100% of segment value)

	Cost [\$1,000]	Delay [months]
Low	6,000	4
Medium	10,000	6
High	15,000	9

### Significant problem

Frequency		Fatalities	Cost	Delay
1.4%	Low	0	10	0
	Likely	0	200	0.5
	High	0	500	2

### Catastrophic problem

Frequency		Fatalities	Cost	Delay
0.80%	Low	0	6,000	4
	Likely	0	10,000	6
	High	0	15,000	9

## Braddock Dam Risk Assessment

### Hazard Analysis Documentation

Activity/(ies): 3.1.1 General Construction

Prepared HGL

Hazard: a+b. Construction Engineering problem

Date 6/5/01

- Reference:** Statistics of historic projects – presented within the Braddock Dam risk analysis.
- Methodology:** The occurrences of construction engineering errors that cause significant problems are treated as one hazard that covers the entire project. The occurrence probability is based on statistics on similar concrete projects using float-in installation technique (offshore platforms, floating vessels, floating bridges, docks and piers, foundation caissons, submerged tunnels, locks and dams). Definition of errors is based on problems that may expose the project to complete loss of the structure or parts thereof, and this is also the basis of the referenced statistics. The statistics are applied directly to present project to determine the probability of errors, and consequences are assessed in terms of loss of one or both of the Braddock Dam segments.
- Assumptions:** Identification of specific engineering construction errors that would present a hazard in the floating state (launching, tow, outfitting, positioning, and setdown) is not attempted. Elimination of such errors is an integral part of the construction planning process. It is not realistic to assume that a more successful identification of such construction engineering errors could be made in the framework of the risk analysis. The risk analysis thus assumes that all possible precautions have been taken to capture errors.
- Occurrence:** Various categories of structures are considered in the historic project statistics, and some may appear more similar to the Braddock Dam project than others. However, to avoid subjective bias on the utilization of the statistics, the compound number for all project types is adopted. The probability of engineering construction errors that will present a significant hazard to the project is 1.1%. In one third of those situations (corresponding to an absolute probability of 0.4%), complete loss of the structure (here, the segments) may result.
- Consequences:** Loss of both segments is not considered relevant because of the sequential project schedule. If significant problems arise with the first segment, the second segment can be changed to avoid the same problem before it reaches the stage where the problem emerged on the first segment. If the first segment is safely installed, only the second can be lost or severely damaged.
- With reference to the statistical basis, the consequences of a “Significant problem” are judged as follows:
- **Cost:** equivalent to 5% of the value (construction investment) of one segment at the time of setdown
  - **Delay:** 1-month delay
- and the consequences of a “Catastrophic problem” are judged as follows:
- **Cost:** ranging between the value (construction investment) of one segment at launch and setdown, respectively
  - **Delay:** 6-month delay
- The above are considered likely consequences. A suitable range around the likely values has been judged to indicate the expected uncertainty.

# Braddock Dam Risk Assessment

## Hazard Analysis Calculations

Activity/(ies): 3.1.1 General Construction

Prepared HGL

Hazard: c+d: Construction contractor problem with significant or catastrophic consequences

Date 6/5/01

### Statistics on engineering construction problems:

**Table 5** Frequencies of construction contractor mistakes on projects with significant or catastrophic consequences

Project type	Segments Installed	Const. problem	Frequency
Offshore platforms	44	2	5%
Floating vessels, bridges, docks	107	0	<1%
Locks and dams	8	0	<13%
Immersed and floating tunnels	365	1	0.3 %
All projects	524	3	0.6%

**Table 6** Segments installed and an upper bound on the occurrence frequency of unit catastrophic loss due to construction contractor mistakes.

Project type	Segments Installed	Const. problem	Frequency of loss
Offshore platforms	44	1	2%
Floating vessels, bridges, docks	107	0	<1%
Locks and dams	8	0	<13%
Immersed and floating tunnels	365	0	<0.3%
All projects	524	1	0.2%

### Occurrence probability (for two segments)

Contractor construction error causing a significant problem	0.8%
Contractor construction error causing catastrophic problem (loss)	0.4%

### Consequences

		Cost [\$1,000]	Delay [months]
Significant problem	Low	10	0.0
	Medium	200	0.5
	High	500	2.0
		Cost [\$1,000]	Delay [months]
Catastrophic problem (loss) (~100% of segment value)	Low	6,000	4
	Medium	10,000	6
	High	15,000	9

### Significant problem

### Catastrophic problem

Frequency		Fatalities	Cost	Delay	Frequency		Fatalities	Cost	Delay
0.80%	Low	0	10	0	0.40%	Low	0	6,000	4
	Likely	0	200	0.5		Likely	0	10,000	6
	High	0	500	2		High	0	15,000	9

## Braddock Dam Risk Assessment

### Hazard Analysis Documentation

Activity/(ies): 3.1.1 General Construction

Prepared HGL

Hazard: c+d: Construction contractor problem with significant or catastrophic consequences

Date 6/5/01

**Reference:** Statistics of historic projects – presented within the Braddock Dam risk analysis.

**Methodology:** The occurrences of construction contractor errors that lead to problems during the construction are treated as one hazard that covers the entire project. The occurrence probability is based on statistics on similar concrete projects using float-in installation technique (offshore platforms, floating vessels, floating bridges, docks and piers, foundation caissons, submerged tunnels, locks and dams). Definition of construction contractor errors as a hazard is based on problems that may expose the project to complete loss of the structure or parts thereof, and this is also the basis of the referenced statistics. The statistics are applied directly to present project to determine the probability of errors, and consequences are assessed in terms of loss of one or both of the Braddock Dam segments.

**Assumptions:** Identification of specific construction contractor errors that would present a hazard in the critical stages (launching, tow, outfitting, positioning and setdown) is not attempted. Elimination of such errors is an integral part of the design process. It is not realistic to expect a more successful design review and error detection to be made in the framework of the risk analysis. The risk analysis thus assumes that all possible precautions have been taken to prevent errors.

**Occurrence:** Various categories of structures are considered in the historic project statistics, and some may appear more similar to the Braddock Dam project. However, to avoid subjective bias on the utilization of the statistics, the compound number for the project types is adopted. The probability of errors that will present a significant hazard to the project is thus 0.6%. In one third of those situations (corresponding to an absolute probability of 0.2%), complete loss of the structure (here, the segments) may result.

**Consequences:** Loss of both segments is not considered relevant because of the sequential project schedule. If significant problems arise with the first segment, the second segment can be changed to avoid the same problem before it reaches the stage where the problem emerged on the first segment. If the first segment is safely installed, only the second can be lost or severely damaged.

With reference to the statistical basis, the consequences of a “Significant problem” are judged as follows:

- **Cost:** equivalent to 5% of the value (construction investment) of one segment at the time of setdown
- **Delay:** 1-month delay

and the consequences of a “Catastrophic problem” are judged as follows:

- **Cost:** ranging between the value (construction investment) of one segment at launch and setdown, respectively
- **Delay:** 6-month delay

The above are considered likely consequences. A suitable range around the likely values has been judged to indicate the expected uncertainty.

# Braddock Dam Risk Assessment

## Hazard Analysis Calculations

Activity/(ies): 2.6.3 Passage of bridges (20 bridges)

Prepared HGL

Hazard: Collision to bridge pier

Date 6/5/01

### Parameters

Segment width	106.2'	Segment length	333.1'
Aberrancy rate	5.3E-4	Passages, N	2 (two segments)
Pier width (typ)	30.0'		

Bridge	Span	Exposure	P <sub>G</sub>	R <sub>B</sub>	R <sub>C</sub>	R <sub>XC</sub>	R <sub>D</sub>	P <sub>Collision</sub>
Sewickley	724.0'	2 main piers	18.1%	1.7	1.0	1.0	1.0	3.2E-4
I79	725.0'	2 main piers	18.1%	1.3	1.0	1.0	1.0	2.6E-4
PGH-McKees	750.0'	2 main piers	17.3%	1.2	1.0	1.0	1.0	2.1E-4
Ohio RR	508.0'	2(3) piers	24.3%	1.0	1.0	1.0	1.0	2.6E-4
West End	755.0'	2(3) piers	17.2%	1.3	1.0	1.0	1.0	2.4E-4
Fort Pitt	640.0'	1 pier	10.3%	1.0	1.0	1.0	1.0	1.1E-4
Smithfield	344.0'	2 main piers	28.4%	1.0	1.0	1.0	1.0	3.0E-4
P. A. Transit	351.0'	1(2) main piers	21.2%	1.0	1.0	1.0	1.0	2.2E-4
Liberty	448.0'	1 pier	13.0%	1.0	1.0	1.0	1.0	1.4E-4
South 10th	705.7'	no piers	0.0%	1.7	1.0	1.0	1.0	0.0E0
Birmingham	607.0'	2 main piers	21.5%	1.7	1.0	1.0	1.0	3.8E-4
Mon. Conn. RR	311.0'	2(3) piers	29.1%	1.3	1.0	1.0	1.0	4.1E-4
Glenwood	557.0'	2 main piers	23.0%	1.7	1.0	1.0	1.0	4.1E-4
CSX	453.0'	2 main piers	25.8%	1.7	1.0	1.0	1.0	4.6E-4
Homestead	516.3'	2 main piers	24.1%	1.7	1.0	1.0	1.0	4.3E-4
P. & L. E.	250.0'	2(4) piers	30.2%	1.7	1.0	1.0	1.0	5.3E-4
Union RR	483.0'	2(3) piers	25.0%	1.0	1.0	1.0	1.0	2.7E-4
Rankin	505.3'	2 main piers	24.4%	1.0	1.0	1.0	1.0	2.6E-4
Union RR	378.0'	Half of bridge	13.8%	1.7	1.0	1.0	1.0	2.4E-4
Conrail RR	393.0'	Half of bridge	13.6%	1.7	1.0	1.0	1.0	2.4E-4

Σ 5.7E-3

Scenario	Relative Probability	Fatalities	Cost [1000\$]	Delay [Months]
<i>Small impact</i>	65%			
Minor damage to the segment		0	8	0
Minor damage to the bridge		0	5	0
Σ		0	13	0
<i>Moderate impact</i>	34%			
Some damage to the segment		0	80	0.5
Minor damage to the bridge		0	5	0
Σ		0	85	0.5
<i>Severe impact</i>	1%			
Complete loss of segment		1	8,000	12
Some damage to the bridge		2	1,000	0
Σ		3	9,000	12

Type	Frequency	Fatalities	Cost	Delay
Minor	3.7E-3	0	13	0
Moderate	1.9E-3	0	85	0.5
Severe	5.7E-5	3	9,000	12

## Braddock Dam Risk Assessment

### Hazard Analysis Documentation

Activity/(ies): 2.6.3 Passage of bridges (20 bridges)

Prepared HGL

Hazard: Collision to bridge pier

Date 6/5/01

- Reference:** *Guide Specification and Commentary for Vessel Collision Design of Highway Bridges*, AASTO, February 1991.  
*Barge Collision Design of Highway Bridges*, Whitney, M.W., Harik, I.E., Griffin, J.J., and Allen, D.L., ASCE Journal of Bridge Engineering, Vol 1, No. 2, May 1996.
- Methodology:** The above reference refers to ships and barge tows, and the segment tows are considered as a barge tow. The size of the largest segment is used for the geometric of the collision calculation.
- Assumptions:** All bridges are included in the collision frequency calculation. Only collisions to the main piers bounding the span are considered. A pier width of 30 ft is generally assumed. Reduction of the collision frequency is made if one or both main pier(s) is out of the water.
- The geometric probability  $P_G$  is calculated from a normal distribution function centered midspan and using the length of the vessel (here, the segment length) as the standard deviation. The probability calculated represents the positions where the segment (considering its width) overlaps with the piers (considering their widths). Conservatively, the larger length is used for both tows.
- The aberrancy frequency is based on the estimated aberrancy rate for barges on the Ohio River, estimated in Whitney et al. as  $5.3 \times 10^{-4}$ . This base rate is multiplied with appropriate correction factors.
- Correction factors on the aberrancy rate:
- $R_C$ : Accounts for currents (in and across the path). Is generally set to 1.0 due to lack of information.  
 $R_B$ : Accounts for bends. Values (angles) are estimated on basis of navigational maps.  
 $R_D$ : Accounts for traffic density. Since the traffic condition can be controlled during the tow, a low traffic density is assumed. Hence,  $R_D = 1.0$ .
- Consequences:** Consequences are estimated for a "general" bridge. Hence, no specific considerations are made for the implication of a collision to an individual bridge.
- Selection of damage scenarios and their relative frequency is based on engineering judgment.
- Cost of damages to the segment is based on a total value (of construction work) of the segment at the time of the tow of \$8 million. This is the average of the value of Segment 1 (\$10.9 million) and Segment 2 (\$6,575,000). "Severe" impact is assumed to result in total loss of the segment; "moderate" impact is assumed to result in damage corresponding to 1% of the value; and "minor" impact incurs damage equivalent to 0.1% of the value of the segment.

# Braddock Dam Risk Assessment

## Hazard Analysis Calculations

Activity/(ies): 3.7.1 Towing on open river

Prepared HGL

Hazard: a. Grounding

Date 6/5/01

### Probability of grounding or loss of control:

#### Average tow traffic for 1996-97 (pr day)

Dam	Up river		Down river		Total	
	Tows/day	Barges/tow	Tows/day	Barges/tow	Tows/day	Barges/tow
Dashields	6.8	6.7	7.0	6.4	13.8	6.6
Emsworth	7.3	5.9	7.3	5.9	14.5	5.9
LD2	6.1	5.6	6.0	5.6	12.1	5.6
LD3	9.4	3.6	9.4	3.6	18.8	3.6
Average (all)	7.4	5.3	7.4	5.2	14.8	5.3
Target river stretch (Dashields to LD2)						
Average	6.7	6.1	6.8	6.0	13.5	6.0

Total movements during period 9,828

#### Accidents with barges on the stretch during 1996-97

Low 4 (Collisions, Allisions, Groundings and Loss of Control)  
High 7 (All accidents)

#### Accident frequencies pr. passage through the target river stretch

Low	0.041%	<= This is used in the risk assessment as the grounding frequency per segment tow from Leetsdale to the outfitting pier
High	0.071%	

### Occurrence

The above probability for grounding along the tow route is used to calculate the probability of grounding a segment. The following correction factors are applied:

- 2.0 Since two tows are made, one for each segment
- 1/3 The tows are performed in a good time window only, with river traffic closed. The tows have been rehearsed in practice.

Resulting frequency of grounding:  $2 \times 1/3 \times 0.041\% = 0.027\%$

### Consequences

	Cost [\$1,000]	Delay [months]
Optimistic judgment	0	0.1
Likely judgment	10	0.3
Pessimistic judgment	50	1

Frequency		Fatalities	Cost	Delay
2.7E-4	Low	0	0	0.1
	Likely	0	10	0.3
	High	0	50	1

## Braddock Dam Risk Assessment

### Hazard Analysis Documentation

Activity/(ies): 3.7.1 Towing on open river

Prepared HGL

Hazard: a. Grounding

Date 6/5/01

#### Reference:

**Methodology:** Grounding frequency is estimated on basis of accident and traffic statistics for the route. Consequences are based on judgment.

**Basis** U.S. Waterway Traffic Data for Ohio and Monongahela Rivers – Lock Statistics:  
<ftp://www.wrsc.usace.army.mil/pub/ndc/lpms/dbf/vess>  
U.S. Coast Guard Accident Statistics:  
<http://www.uscg.mil/hq/g-m/moa/docs/vdb.exe>

**Assumptions:** The segment tow is assumed equivalent to a normal barge tow. Hence, the accident rate is established for barge tow traffic only.

**Consequences:** Severe damage in a grounding event is not considered likely. The cost and delay consequences are judged relative to the time and cost associated with the segment at the time of the tow. Fatalities are not considered likely at all.



# Braddock Dam Risk Assessment

## Hazard Analysis Calculations

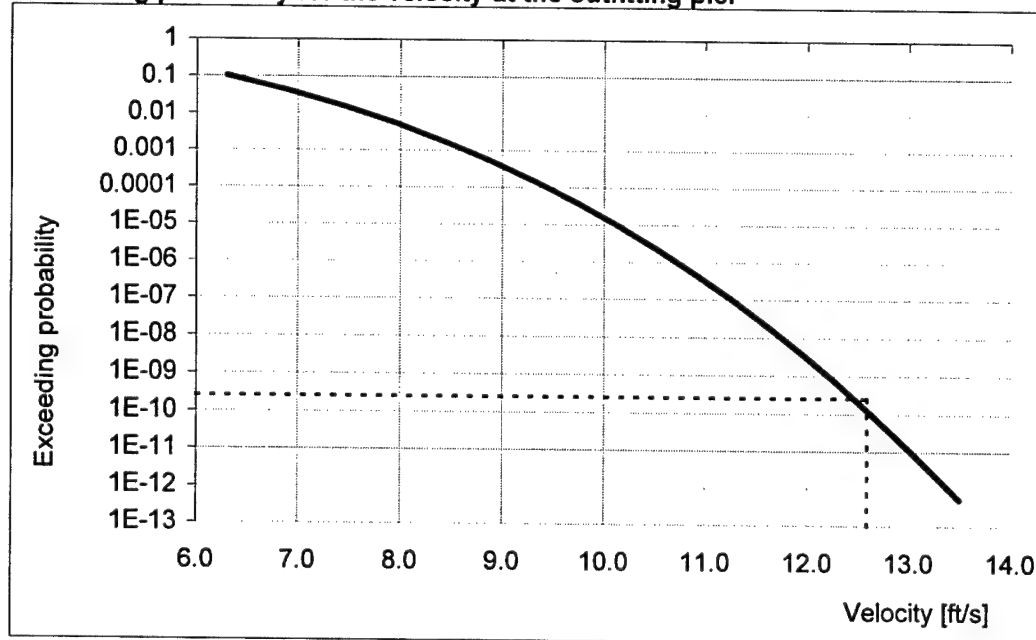
Activity/(ies): 3.7.1 Outfitting (both segments), General

Prepared HGL

Hazard: e. Contingency mooring failure during high river stage.

Date 6/5/01

### Exceeding probability for the velocity at the outfitting pier



A total - or effective - safety factor on the mooring capacity of 2 is assumed. Consequently, mooring failure is assumed to occur when the drag force reaches 2 times the design drag. In terms of the velocity, this means that failure occurs when the velocity is 1.4 times the design velocity.

### Occurrence

Velocity at overload  $(1.4142 \times 8.9)$

12.6 ft/sec

Corresponding return period  $T_{\text{failure}}$

1.97E+09 years

Exposure period  $T_{\text{exposure}} = 2 \times 3$  months (3 for each segment)

0.5 year

Exceeding probability  $(\sim T_{\text{exposure}} / T_{\text{failure}})$

2.542E-10

### Consequences

Even with the maximal consequences of a mooring failure, the risk is negligible because of the very low occurrence probability. No fatalities are assumed to result, and cost and delays are based on judged fractions of the value of the segment.

	Cost [\$1,000]	Delay [months]
Optimistic judgment	0	0
Likely judgment	100	1
Pessimistic judgment	15000	7

Frequency		Fatalities	Cost	Delay
2.5E-10	Low	0	0	0
	Likely	0	100	1
	High	0	15,000	7

## Braddock Dam Risk Assessment

### Hazard Analysis Documentation

Activity/(ies): 3.7.1 Outfitting (both segments), General

Prepared HGL

Hazard: e. Contingency mooring failure during high river stage.

Date 6/5/01

Reference: River stage and velocity statistics received from Ray Povirk 4/8/98.

Methodology: Approximation of the river velocity statistics allows development of the probability of exceeding a certain velocity during the period when the segment is moored at the outfitting pier (~3 months). Assuming that the mooring force (drag) is proportional to the square of the velocity, it is then possible to determine the probability of mooring failure based on an assumed factor of safety in the mooring system.

Note that the statistical basis (observations) probably covers only about 100 years. So, the estimation of events with a return period of more than 1 million years represents a significant and theoretical extrapolation of the observations.

Assumptions: The factor of safety in the mooring system is assumed to exceed 2.0. Simple overloading is assumed governing for this failure mode. Possibility of damage to the mooring line or -point, incorrect attachment, or other types of nonconformance are not included in the assessment.

Consequences: The value of the segments based on the total value of construction work at the time of the failure ranges from \$7 million to \$17 million depending on the completion level of the work to be done at the outfitting pier.

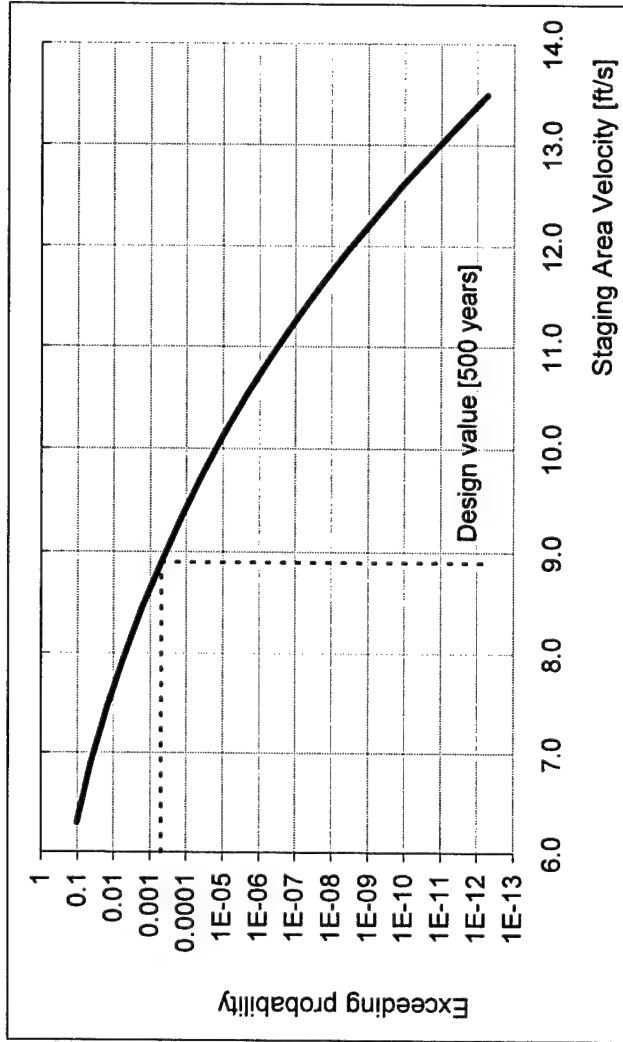
# Probability distribution of drag load at Outfitting pier

$T_0$  0.25 year  
(Period while segment is at the outfitting pier)

Approximating relations  
(Staging Area Vel)<sup>3</sup> = 84.81Ln(T) + 179.03  
T=EXP(((Staging Area Vel)<sup>3</sup>-179.03)/84.81)

T [years]	Vel [ft/s]	P <sub>Exceedance</sub>	Drag Load
2.3	6.3	10.35%	x0.50
5.8	6.9	4.24%	x0.60
15.8	7.4	1.57%	x0.70
46.4	8.0	0.54%	x0.80
146.4	8.4	0.17%	x0.90
493.4	8.9	0.051%	Design Load
1,770	9.3	0.014%	x1.10
6,741	9.7	0.004%	x1.20
27,169	10.1	9.20E-06	x1.30
115,664	10.5	2.16E-06	x1.40
519,062	10.9	4.82E-07	x1.50
2,451,048	11.3	1.02E-07	x1.60
1.22E+7	11.6	2.06E-08	x1.70
6.33E+7	11.9	3.95E-09	x1.80
3.45E+8	12.3	7.25E-10	x1.90
1.97E+9	12.6	1.27E-10	x2.00
1.17E+10	12.9	2.13E-11	x2.10
7.30E+10	13.2	3.43E-12	x2.20
4.74E+11	13.5	5.28E-13	x2.30

Note: The factor on the Velocity is the square root of the factor on the load.



# Braddock Dam Risk Assessment

## Hazard Analysis Calculations

Activity/(ies): 3.7.1 Outfitting (both segments), General

Prepared HGL

Hazard: f. Exposed to river flood. Access for corrective action may not be possible.

Date 6/5/01

Segment overtops the pier and is damaged when stage drops.

### Exceeding probability for river stage at outfitting pier

Exposure period,  $T_0$  0.5 years (3 months per segment totals to 6 months or 0.5 year)

#### Provided statistics

T [years]	Pool [ft]	P <sub>Exceedance</sub>
0.125	725.5	98.17%
0.25	727.4	86.47%
0.5	729.3	63.21%
1	729.4	39.35%
2	731.3	22.12%
5	734	9.516%
10	736	4.877%
20	737.7	2.469%
50	740.2	0.995%
100	742	0.499%
200	743.8	0.250%
500	746.2	0.100% <- Design
1000	748	0.050%

#### Convolution of fender failure probability

T [years]	Pool [ft]	P <sub>Exceedance</sub>	P <sub>Failure</sub>	P <sub>Combined</sub>
545	746.2	0.0918%	0%	0.0000%
810	747.2	0.0617%	10%	0.0020%
1204	748.2	0.0415%	20%	0.0027%
1791	749.2	0.0279%	30%	0.0027%
2662	750.2	0.0188%	40%	0.0025%
3959	751.2	0.0126%	50%	0.0021%
5887	752.2	0.0085%	60%	0.0017%
8753	753.2	0.0057%	70%	0.0013%
13016	754.2	0.0038%	80%	0.0010%
19354	755.2	0.0026%	90%	0.0008%
28779	756.2	0.0017%	100%	0.0017%

Σ 0.0185%

### Occurrence

Event tree describing the various scenarios

Fender Failure P=1.8e-4	Remedy attempted before level drops P=0.900		Remedy successful P=0.900	No consequences P=1.5e-4
			Not successful P=0.100	Lands on top of pier P=8.3e-6
				Stays clear P=0.500
				No consequences P=8.3e-6
	No action P=0.100		Lands on top on pier P=0.500	Lands on top of pier P=9.2e-6
			Stays clear P=0.500	No consequences P=9.2e-6

The combined probability of the segment landing on the pier is 1.76E-05

### Consequences

	Cost [\$1,000]	Delay [months]
Optimistic judgment	0	0
Likely judgment	7000	2
Pessimistic judgment	15000	7

Frequency		Fatalities	Cost	Delay
1.8E-5	Low	0	0	0
	Likely	0	7,000	2
	High	0	15,000	7

## Braddock Dam Risk Assessment

### Hazard Analysis Documentation

Activity/(ies): 3.7.1 Outfitting (both segments), General

Prepared HGL

Hazard: f. Exposed to river flood. Access for corrective action may not be possible.  
Segment overtops the pier and is damaged when stage drops.

Date 6/5/01

- Reference:** River stage and velocity statistics received from Ray Povirk 4/8/98.
- Methodology:** Approximation of the river stage statistics allows development of the probability of exceeding a certain level during the period when the segment is moored at the outfitting pier (~3 months).
- Basis** The design requirements specify that extended vertical fenders shall be provided that are able to hold the segment clear of the pier for the 500-year return period level. At the design level, the specifications also require that the extended fenders shall provide at least 10 ft contact length with the element. Since the draft of the segment ranges from 10 to 15 ft, the river stage shall exceed the design stage by 10 to 15 ft for the segment to overtop the fender.
- However, because the location of the load from segment will move upward as the river stage rises, overloading of the fender may occur before the segment fully overtops the fenders.
- Assumptions:** The probability that the extended fender fails at a certain level is assumed to vary linearly from 0 at the design stage to 1.0 at design stage + 10 ft. It is also assumed that the pier top level will be at least 15 ft below design stage level such that segment overtopping of the pier is possible whenever the design stage level is exceeded.
- Consequences:** The value of the segments based on the total value of construction work at the time of the failure ranges from \$7 million to \$17 million depending on the completion level of the work to be done at the outfitting pier. If the segment ends up resting on the pier, the damage is assumed in the range from 50% of the value (segment being repairable) to 100% of the value.

Assessment of probability of exceeding a certain staging area pool level (Outfitting pier)

T<sub>0</sub> 0.25 year  
(Period while segment is at the outfitting pier)

T [years]	Pool [ft]	Approx.	P <sub>Exceedance</sub>
0.125	725.5	725.1	86.47%
0.25	727.4	726.8	63.21%
0.5	729.3	728.6	39.35%
1	729.4	730.3	22.12%
2	731.3	732.1	11.75%
5	734	734.4	4.877%
10	736	736.1	2.469%
20	737.7	737.9	1.242%
50	740.2	740.2	0.499%
100	742	741.9	0.250%
200	743.8	743.7	0.125%
500	746.2	746.0	0.050%
1000	748	747.7	0.025%

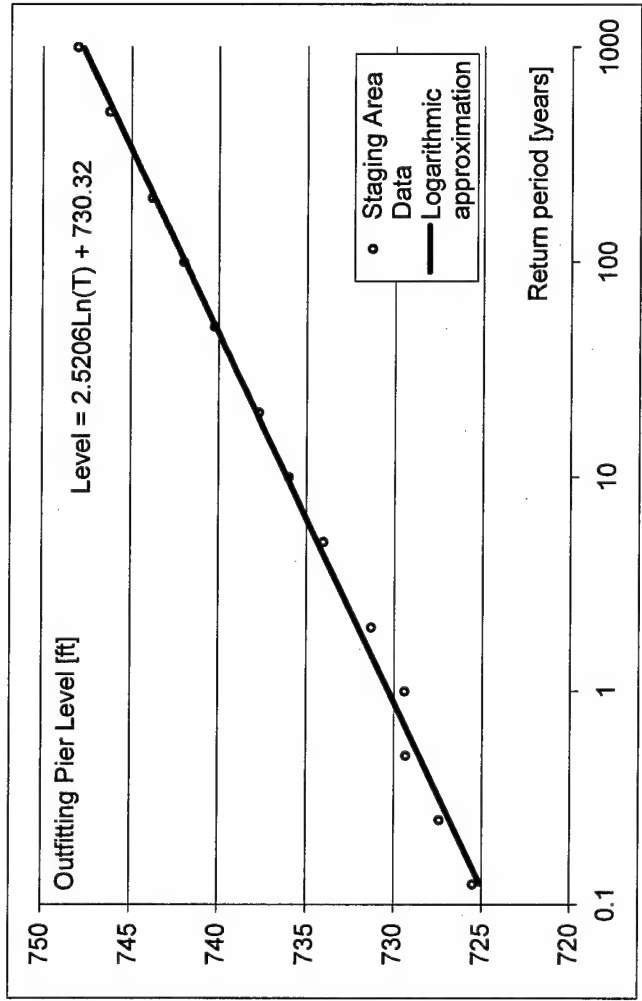
Design ->

Extrapolations

Design+0ft	500	-	746.0	0.0500%
Design+2ft	1106	-	748.0	0.0226%
Design+4ft	2444	-	750.0	0.0102%
Design+6ft	5405	-	752.0	0.0046%

Approximating relations

Staging Area Pool =  $2.5206 \ln(T) + 730.32$   
 $T = \text{EXP}((\text{Staging Area Pool} - 730.32) / 2.5206)$



# **Appendix C**

## **Marine Construction Problems and Accidents**

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The following is a listing and categorization of actual problems and failures that have been encountered on concrete marine projects with construction methods of a nature similar to the Braddock Dam project.

# Historical Experience with float-in type concrete structures

## Problem categories

- P: Problem that was solvable and did not have catastrophic consequences  
(Consequence class – Medium)  
C: Problem with catastrophic consequences (loss of structural elements)  
(Consequence class—High)

## Cause categories

- ED: Engineering Design Inadequacy  
EC: Construction Engineering Problem  
CC: Construction Contractor Mistake

## Offshore Platforms – Temporally Afloat

(Floating either during transport and installation or permanently)

Platform	Problem Category	Cause Category	Units Total	Units Lost
Seatank Prototype	C	CC	1	1
Ekofisk			1	
Ekofisk Barrier Wall	P	ED	2	
Beryl A	P	EC	1	
Brent B			1	
Statfjord A	P	EC	1	
Statfjord B			1	
Statfjord C			1	
Ninian Central	P	CC	1	
Ravenspurn			1	
Draugen			1	
Gullfaks A			1	
Gullfaks B			1	
Gullfaks C			1	
Sleipner I	C	EC/ED	1	1
Sleipner II			1	
Troll A			1	
Troll B			1	
Frigg CDP1			1	
Brent D			1	
Frigg TP1	C	EC	1	
Frigg MP2	P	ED	1	
Dunlin A			1	
Frigg TCP2			1	
Oseberg A			1	
German Seafloor Tank			1	
Harding			1	
Heidrun			1	
Hay Point Terminal	P	EC	3+4	
2 Platforms in Brazil			2	
CIDS			1	
Hibernia			1	
Wandoo (NW Shelf, Australia)			1	
Malanpaya			1	
Tuna (Bass Strait, Australia)			1	
Bream (Bass Strait, Australia)			1	

## Floating Vessels, Bridges, Docks

(Initial transport and service only – not including long-term performance afloat)

Structure	Problem Category	Cause Category	Units Total	Units Lost
Lake Washington 1 Lacey V Murrow	**C	ED	10	4
Lake Washington 2 Evergreen Point	**P	ED	12	
Lake Washington 3			8	
Hood Canal 1	**C	ED	12	6
Hood Canal 2			6	
Hobart Bridge Tasmania	**C	ED	8	8
Lake Okanagan Bridge B.C.			6	
Admiral Clary Bridge			5	
Great Belt East Bridge Caissons			4	
Rion Antirion Bridge			4	
WW2 Oil Storage Tankers and ships			15	
Ardjuna Sakti LPG Storage Barge			1	
WW1 Grain Vessels			6	
Valdez Floating Container Terminal			2	
Ferry Docks			2	
Seaplane Docks			3	
N'Kossa			1	
Russian Floating Docks			2	

\*\* Problem occurred in-service – Data excluded from this study due to lack of similarity with innovative construction projects.

## Locks and Dams

Structure	Problem Category	Cause Category	Units Total	Units Lost
Montezuma Slough	P	ED/EC	3	1 salvaged
Neva River Salinity Barrier St Petersburg			4	
Kislogbusk Tidal Power Station Murmansk			1	



An asterisk indicates Ben C. Gerwick direct involvement and thus familiarity with project details and problems

### Immersed and Floating Tunnels

Structure	Problem Category	Cause Category	Units Total	Units Lost
Freidrichshafen Germany			2	
Posey St. Alameda, CA	*		12	
Havana Tunnel Cuba			5	
Massey (Deas Is.) Vancouver, BC	*		6	
Rendsburg Germany			1	
Webster St. Alameda, CA	*		12	
Liljeholmsviken Sweden			1	
Haneda Tunnel Japan			1	
Coen Tunnel Netherlands			6	
Wolfburg Tunnels Germany			2	
Benelux Rotterdam Netherlands			8	
Lafontaine Tunnel Canada *			7	
Rotterdam Metro Tunnels Netherlands	*		36	
Ij Tunnel Netherlands			9	
Scheldt E3 (JFK Tunnel) Belgium			5	
Heinenoord Tunnel Netherlands			5	
Limfjord Tunnel Denmark			5	
Parana Tunnel Argentina			36	
Elbe Tunnel Germany			8	

### Immersed and Floating Tunnels

Structure	Problem Category	Cause Category	Units Total	Units Lost
Vlaque Tunnel Netherlands			2	
Tokyo Port Tunnel Japan *			9	
Prinses Margriet Tunnel Netherlands			1	
Drecht Tunnel Netherlands			3	
Kil Tunnel Netherlands			3	
Hong Kong Mass Transit Tunnel Hong Kong			14	
Hemspoor Tunnel Netherlands			7	
Botlek Tunnel Netherlands			5	
Tokyo Port Daiinikoro Tunnel Japan			6	
Rupel Tunnel Belgium			3	
Metropolitan Rail Tunnel (Main) Germany			2	
Bastia Old Harbour Tunnel France			4	
Spijkenisse Metro Tunnel Netherlands			6	
Coolhaven Tunnel Netherlands			7	
Kaohsiung cross Harbour Tunnel Taiwan			6	
Guldborgsund Tunnel Denmark			2	
Ernstunnel Germany			5	
Marie Tunnel France			7	
Zeeburger Tunnel Netherlands			3	

**Immersed and Floating Tunnels**

Structure	Problem Category	Cause Category	Units Total	Units Lost
Eastern Harbour Crossing Hong Kong *			15	
Conwy Tunnel United Kingdom			6	
Liefkenshoek Tunnel Belgium			8	
Willemspoortunnel Netherlands			8	
Tama River Tunnel Japan			12	
Kawasaki Fairway Tunnel Japan			9	
Sydney Harbour Tunnel Australia *			8	
Bilbao Metro Line Spain			2	
Medway Tunnel United Kingdom			3	
Schiphol Rwy Tunnel Netherlands			4	
Oresund Denmark *	P	CC	20	
Suez (Service problems)	P	ED	4	
Abu Dabi (Service problems)	P	ED	4	

Various indicative statistics can be derived from the above summary of projects. The categories used for problem causes are:

- ED Engineering design inadequacies for permanent or temporary structures that typically represent a systemic problem associated with the project and not necessarily the individual segment (one calculation for all segments).
- EC Construction engineering problems for individual permanent or temporary structures that typically represent a random problem with an equal occurrence probability on each segment.
- CC: Covers Contractor construction problems in production and/or installation of a particular segment, e.g. random error.

The estimates of the frequency of design inadequacies (ED) are calculated as the number of projects with this type of inadequacy divided by the total number of projects.

**Table 1** Frequencies of engineering design problems on projects with significant or catastrophic consequences.

Project type	Total Projects	Eng. problem	Frequency
Offshore platforms	36	3	8%
Floating vessels, bridges, docks	18	0	<6%
Locks and dams	3	1	33%
Immersed and floating tunnels	51	2	4%
All projects	108	6	5.6%

**Table 2** Frequencies of engineering design problems on projects with catastrophic consequences.

Project type	Total Projects	Eng. problem	Frequency
Offshore platforms	36	1	3%
Floating vessels, bridges, docks	18	0	<6%
Locks and dams	3	0	<33%
Immersed and floating tunnels	51	0	<2%
All projects	108	1	0.93%

The project statistic thus leads to a frequency of engineering inadequacies resulting in a loss (catastrophic consequences) that ranges from <2% to <33% depending on project type. An overall frequency of 0.93% is obtained for all projects.

The estimates of the frequency of construction engineering problems (EC) are calculated as the number of segments or units with problems divided by the total number of segments or units.

Table 3 Frequencies of construction engineering problems on projects with significant or catastrophic consequences.

Project type	Segments Installed	Eng. problem	Frequency
Offshore platforms	44	5	11%
Floating vessels, bridges, docks	107	0	<1%
Locks and dams	8	1	13%
Immersed and floating tunnels	365	0	<0.3%
All projects	524	6	1.1%

Table 4 Frequencies of construction engineering problems on projects with catastrophic consequences.

Project type	Segments Installed	Eng. problem	Frequency
Offshore platforms	44	2	5%
Floating vessels, bridges, docks	107	0	<1%
Locks and dams	8	0	<13%
Immersed and floating tunnels	365	0	<0.3%
All projects	524	2	0.4%

The project statistic for the frequency of construction engineering problems resulting in a high loss (catastrophic) consequence ranges from <0.3% to <13% depending on project type. An overall catastrophic consequence frequency of 0.4% is obtained for all segments or units installed.

Project statistics for Contractor Construction (CC) or installation mistake frequencies are shown in Tables 5 and 6. The occurrence frequencies are based on the number of segments with construction contractor problems divided the total number of segments or units considered.

Table 5 Frequencies of construction contractor mistakes on projects with significant or catastrophic consequences.

Project type	Segments Installed	Const. problem	Frequency
Offshore platforms	44	2	5%
Floating vessels, bridges, docks	107	0	<1%
Locks and dams	8	0	<13%
Immersed and floating tunnels	365	1	0.3%
All projects	524	3	0.6%

With respect to loss due to construction mistakes, it is relevant to consider the total number of segments or units produced and installed. Where the project sample base for a type of structure does not include projects where a mistake in the construction or installation process has resulted in a unit loss, the sample projects can therefore provide only an upper bound for the occurrence frequency.

Table 6 Segments installed and an upper bound on the occurrence frequency of unit catastrophic loss due to construction contractor mistakes.

Project type	Segments Installed	Const. problem	Frequency of loss
Offshore platforms	44	1	2%
Floating vessels, bridges, docks	107	0	<1%
Locks and dams	8	0	<13%
Immersed and floating tunnels	365	0	<0.3%
All projects	524	1	0.2%

The project statistic for the frequency of construction contractor mistakes resulting in a high loss (catastrophic) consequence that ranges from <0.3% to <13% depending on project type. An overall frequency of 0.2% is obtained for all segments or units produced and installed.

For application in the Braddock Dam risk analysis, the above can be used to provide indicative frequencies for the following hazards:


- Engineering design inadequacies and construction engineering problems that expose segments to instability and structural failures during float-out and installation. Examples are in float-out stability calculations and in design of temporary structures (bulkheads and bracing).
- Construction Contractor mistakes in establishment of facilities, in fabrication of the segments, in execution of the tows, in execution of the installation, in the contingency planning, etc.

Both categories of hazards can be difficult to analyze explicitly because of the number of possibilities for various problems. The frequencies derived above are therefore useful indicative quantities.

Establishment of an innovative construction similar project database by gathering experience on Corps of Engineers projects would provide a useful extension of the statistical base for these types of hazards.

# PROBLEMS AND ACCIDENTS ON PAST "IN - THE - WET" CONSTRUCTION

EVENT	STAGE	RESPONSIBILITY AND CAUSE	CONSEQUENCES	MITIGATION OR REPAIRS CARRIED OUT	PREVENTION IN FUTURE
MONTESUMA SLOUGH, FANTER GATE INSTALLATION	INSTALLATION	CONTRACTOR'S NAVAL ARCHITECTURE CAPSIZING DURING INSTALLATION	TIPPED 45° - THEN GROUNDED ON MAD BANK (LUCKY !!)	CONTROLLED BALLASTING IN CELLS - CRANE BARGE ENABLED 100% SALVAGE	CALCULATE ON AT EACH STAGE - REINFORCE CELLS FOR DIFFERENTIAL HEAD.
BERYL A CELL WALLS, EXTENSIVE WIDE CRACKS	FABRICATION AFLOAT	CONTRACTOR DIFFERENTIAL BALLASTING OF ADJACENT CELLS, ASSUMED UNIMPORTANT	CRACKS UP TO 6" WIDE DELAY IN JOB 3 MONTHS EXTRA COST \$3M	MAJOR CONCRETING AND EPOXY INJECTION	MUST EVALUATE BALLASTING AT EVERY STAGE BY DESIGNER
ENGISK ON CAISSON - CRACKS IN EXTERNAL WALLS	FABRICATION AFLOAT	EXTERNAL HYDROSTATIC HEAD EXCEEDED STRUCTURAL CAPACITY, DESIGNER	MAJOR CRACKREPAIR BY EPOXY	DEBALLASTED TO REDUCE HYDROSTATIC HEAD	MUST EVALUATE DRAFT AT EVERY STAGE, BY DESIGNER
TARSUIT CAISSON - THERMAL CRACKS IN WALL	FABRICATION	CONTRACTOR - COLD, DRY WINDS ON YOUNG CONCRETE	EXTENSIVE CRACKS LATER WIDENED BY ICE JACKING	NONE	BLANKETING YOUNG CONCRETE SURFACES
TARSUIT CAISSON - STRUCTURAL CRACKS	INSTALLATION	CONTRACTOR - LANDED CAISSON SETTING ON TIPPED BASE - DUE TO SURVEY ERROR	LARGE CRACKS, LATER WIDENED BY ICE JACKING	NONE	REDUNDANT SURVEYS FOR POSITIONING, EASILY INTERPRETED.
NRMAN CAISSON - BLOCKED PRESTRESSING DUCTS	FABRICATION	CONTRACTOR - CONCRETE PUSHED REBAR ONTO DUCTS, SPLICES IMPEDED TENDONS	PREVENTED THREADING OF TENDONS	EXTENSIVE SUPPLEMENTAL PRESTRESSING	BETTER SPLICES OF DUCTS, SADDLES UNDER REBAR CROSSING DUCTS
TSING MA BRIDGE, MA WAY TOWER CAISSON, LOCK OF CONCRETE UNDER UPPER SLAB	PLACEMENT OF TREMIE CONCRETE	DESIGNER AND CONTRACTOR NO SLOPE TO UNDERSIDE, NO PROVISION FOR FLOW	GAPS UNDER UPPER SLAB	REMEDIAL GROUTING	SLOPING UNDERSIDE AND BETTER CONCRETE MIX, ADDITIONAL HEAD
GENOA (IN NAVAL) CONCRETE FLOATING DRYDOCK	INITIAL SERVICE TESTS	DESIGNER - STIFF UPPER WALLS TOOK ALL MEMBRANE SHEAR	MAJOR MEMBRANE SHEAR CRACKS, STRUCTURE CONSUMED AND ABANDONED	STRUCTURE DEEMED UNREPAIRABLE	MEMBRANE SHEAR OFTEN CRITICAL ON THIS TYPE OF STRUCTURE
NRMAN CENTRAL PLATFORM, FLOODING OF OUTER CELLS	CONSTRUCTION AFLOAT	CONTRACTOR - TEMPORARY PLUGS REBAR INTO CELLS, CAUSING CYCLE FATIGUE	SIGNIFICANT LIST CAUSED ADJACENT CONCRETE TO SINK, 3 CAUSED LOSS OF PLATFORM AND NOT INNER BULKHEADS HELD	BULKHEADS REPAIR	DOUBLE NUTS ON ALL PLUGS, REINFORCE PLUGS, LARGER BOLTS REINFORCE INTERNAL BULKHEADS TO PREVENT PROGRESSIVE COLLAPSE
STAIF JORD BASE RAFT	FLOAT OUT	DESIGNER HAD NOT CHECKED THIN BUT LARGE BASE RAFT FOR ECCENTRIC MOMENTS	OVERBURST CAUGHT AT LAST MINUTE, DELAY OF 2 WEEKS	CHANGED BALLASTING AND AIR CUSHIONING	PROVIDE REBAR AND PS IN TOP OF BASE RAFT
EVERGREEN POINT FLOODING BRIDGE	SERVICE	DESIGNER INADEQUATE REBAR ON PORTION SECTIONS FOR POTENTIAL CRACKING	WIDENING CRACKS ON EVERY PORTION CELL	INCREASE PRESTRESSING BY MAJOR EXTERNAL POST TENSIONING	MINIMUM STEEL AREA ACROSS ALL CRACKS, MORE INITIAL PRESTRESS.
SAN MATEO BRIDGE PIERS	TRANSPORT	SMALL HOLES IN DECK ALLOWED RAIN TO FLOOD, CAUSING FREE SURFACE, CONTRACTOR	TALL PRECAST PIER SEGMENTS TIPPED RADICALLY, COLLAPSE IMMINENT BUT DID NOT OCCUR	PUMPED WATER OUT OF CELLS	SEAL ALL HOLES IN DECK TO PREVENT LEAKS
BERYL A CAISSON SHEAR FAILURE POTENTIAL	INSTALLATION	DESIGNER, FEA GRIDS SPANNED CRITICAL AREA	DELAY AND ADDED COST.	ADDED ADDITIONAL RING STRUCTURE	USE CLASSICAL ANALYSES TO IDENTIFY CRITICAL ZONES FOR FEA GRIDS
CREAT BELT WESTERN BRIDGE, CAISSONS - BASE SLAB REINFORCING	DESIGN	OWNERS ENGINEER DEMANDS ADDITIONAL REINFORCEMENT	CLAIM BY CONTRACTOR WHO WON \$100M DUE TO 6 MONTHS DELAY		CLEAR REQUIREMENTS RAPID DISPUTES SETTLEMENT



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 SAN FRANCISCO 94111  
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PROBLEMS AND ACCIDENTS ON PAST  
 "IN - THE - WET" CONSTRUCTION

DATE: \_\_\_\_\_ JOB NO: \_\_\_\_\_ DESIGNED BY: \_\_\_\_\_ DRAWING NO: \_\_\_\_\_  
 1 OF 3

# PROBLEMS AND ACCIDENTS ON PAST "IN - THE - WET" CONSTRUCTION

EVENT	STAGE	RESPONSIBILITY AND CAUSE	CONSEQUENCES	MITIGATION OR REPAIRS CARRIED OUT	PREVENTION IN FUTURE
MAJOR CENTRAL BASE RAFT - COLLAPSE WHILE STRIPPING SUPPORTS	CONSTRUCTION IN BASIN	CONTRACTOR, INK - UP OF FLYASH AND CEMENT IN STORAGE. VERY LOW STRENGTH	NO SERIOUS INJURY. DELAY 1 MONTH	REBUILT BASE RAFT	COLOR CODE BINS AND ALL PIPING. USE DIFFERENT SIZE PIPE
STATFORD A - MAJOR LIST - ALMOST CAPSIZED	CONSTRUCTION AFLOAT	WHILE TESTING, LEFT ONE VALVE OPEN. PUMP RUNNING, ECCENTRIC BALLASTING	WEN ABANDONED PLATFORM. 1 WEEK DELAY	CLOSED VALVE, PUMPED BALLAST BACK	LOOKS ON ALL VALVES WHEN TESTING. HAVE SUPERINTENDANT ON LOCATION TO SUPERVISE
SEAFAR PROTOTYPE CASSON (FRANCE) EXPLOSION	INSTALLATION	DESIGNER - CONTRACTOR INSTABILITY AS DECK SUBMERGED. OVERBALLASTING	CASSON PLUNGED AND IMPLODED. SET FRENCH OFFSHORE PROGRAM BACK		VERIFY ALL STAGES AND HYDRODYNAMIC EFFECTS.
STATFORD A CRACKS IN CELL WALLS	TESTING FOR SUBMERGENCE	DESIGNER - DON'T CONSIDER DEFORMATION OF CASSON WALLS VS. STIFFNESS OF TOP AND BOTTOM OF RAFT	REQUIRED EXTENSIVE REPAIRS PROTECTION FOR CORROSION	EPOXY INJECTION OF CRACKS. REBAR IN CRITICAL SECTIONS. CORROSION PROTECTION IN CELLS	CONSIDERATION OF GLOBAL BEHAVIOR AS GIANT "DRUM"
STATFORD A - CRACK REPAIR OF CELL WALLS	AFLOAT	CONTRACTOR - WHILE REPAIRING CRACKS ABOVE HYDRAULICALLY EXTENDED AND WIDENED CRACKS	MINOR CRACKS BECAME MAJOR CRACKS	REDUCED PRESSURE AND EXTENT OF INJECTION. CORROSION PROTECTION	LAMINAR CRACKS REQUIRE STITCH BOLTS BEFORE INJECTION AND LIMIT ON PRESSURE.
SLEIPNER A PLATFORM IMPOSION (NORWAY)	TESTING FOR SUBMERGENCE	DESIGNER - CONTRACTOR INADEQUATE REBAR IN CRITICAL SHEAR AND TENSION ZONES DUE TO FEA AND CONTRACTOR SHORTENED REBARS TO FACILITATE PLACEMENT	LOSS OF ENTIRE PLATFORM. 1500M CONSEQUENTIAL LOSS	PLATFORM REBUILT WITH ADDED REBAR ON BASIS OF CLASSICAL ANALYSES	USE CLASSICAL ANALYSES TO REVEAL CRITICAL ZONES FOR FEA CONTRACTOR MUST NEVER MODIFY REBAR WITHOUT APPROVAL OF DESIGNERS
BREAKWATER CASSONS SOUTH AFRICA - MISLOCATION	INSTALLATION	CONTRACTOR WATER TRAPPED UNDER CASSON HAS TO ESCAPE, CREATING THRUST	CASSON SET DOWN OFF LOCATION. SCOUR OF SOIL UNDERBASE	ACCEPTED IN THEIR NEW LOCATIONS. REFILLED UNDERBASE	SLOW RATE OF DESCENT OVER LAST 2 METERS.
OFFSHORE TERMINAL TANKWALA CRANE CRACKED HEAVY SEGMENT - LIFTING PLATES FAILED	CONTRACTOR	USED SCRAP STEEL IN LIFTING GEAR WHICH HAD LOW FATIGUE AND CHURNED IMPACT TOUGHNESS. WELDS IN TENSION	1 FATALITY (PROJECT MANAGER) 10 DAYS DELAY TO JOB	SEGMENT WAS ONLY SLIGHTLY DAMAGED	BETTER DESIGN OF LIFTING GEAR AND SELECTION OF MATERIALS. USE WELDS IN SHEAR
HOOD CANAL CONCRETE FLOATING BRIDGE SUNK IN STORM	SERVICE	MAINTENANCE PERSONNEL DESIGNER. CRACKS OPEN MANHOLES LED TO FLOODING OF PONTOONS. (MAINTENANCE PERSONNEL HAD TO OPEN WEEKS FOR PONTONS SO THEY LEFT THEM OPEN)	LOSS OF BRIDGE		VACUATE STEEL AND PRESTRESS BRIDGES THAT CRACKS NEVER FORMED. DO NOT OPEN SOUNDING TUBES.
ORESLAND BRIDGE PIERS - SCOUR UNDER BASE DURING STORM	AFTER INSTALLATION	DESIGNER. INADEQUATE SCOUR PROTECTION AFTER PLACEMENT OF CASSON	MAJOR UNDERMINING DELAYED THAT ELEMENT OF BRIDGE	EXTENSIVE UNDERBASE GROUTING. RERAP	DESIGN SCOUR PROTECTION MORE CONSERVATIVELY
CRACKING FOR FLOATING STRUCTURES LESBIE	WHILE AFLOAT	DESIGNER - CONSTRUCTION JOINTS. - RESTRAINT TO SHORTENING UNDER PRESTRESS - WATERSTOP'S INEFFECTIVE	- FREE SURFACE EFFECTS - EFFECTS ON DRAFT	- SOME CRACKS HEALED AND SELF-SEALED - EPOXY INJECTION EXTERNAL SEALS	MORE RE-STEEL ACROSS JOINTS. BETTER BONDING



**BEN C. GIERWICK, INC.**  
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 801 MARINER DRIVE, SUITE 100  
 SAN FRANCISCO, CA 94111  
 (415) 382-8972

PROBLEMS AND ACCIDENTS ON PAST  
 "IN - THE - WET" CONSTRUCTION

DATE	28 NOV	DESIGNED BY	BGC
		DRAWN BY	2 OF 3

# PROBLEMS AND ACCIDENTS ON PAST "IN - THE - WET" CONSTRUCTION

EVENT	STAGE	RESPONSIBILITY AND CAUSE	CONSEQUENCES	MITIGATION OR REPAIRS CARRIED OUT	PREVENTION IN FUTURE
GENERIC FOR FLOATING STRUCTURES - GROWTH IN WEIGHT AND DRAFT	A FLOAT	CONTRACTOR - DESIGNER - SPREADING OF FORMS SPLICE - WATERSHIPS INEFFECTIVE	- EXCESSIVE DRAFT - INSUFFICIENT FREEBOARD	CHANGE UPPER CONCRETE TO MODIFIED DENSITY	BETTER ACCOUNTABILITY IN DESIGN BETTER CONTROL IN CONSTRUCTION
CRACKING IN COMPRESSION ZONES GENERIC	FABRICATION AND SERVICE	DESIGNER INSUFFICIENT REINFORCEMENT TO PREVENT CRACKING AND CONSTRUCTION STAGES.	CRACKS WHICH DON'T CLOSE, LEAKAGE	EPOXY INJECTION (BUT NOT ALWAYS SUCCESSFUL)	DESIGNER TO CONSIDER THERMAL AND CONSTRUCTION STRESSES
COVE POINT TERMINAL CRACKING PARALLEL TO PRESTRESS	INSTALLATION AND SERVICE	DESIGNER - BURSTING STRESSES, THERMAL STRAINS, DELAYED ETTINGITE OR ASR, SECONDARY STRESSES DUE TO PRESTRESS	CRACKS DON'T CLOSE CORROSION AT CRACKS	- THERMAL ENCLOSULATION - EPOXY INJECTION	LOWER TEMPERATURE IN ACCELERATED CURING, MORE CROSSING REBAR

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PROBLEMS AND ACCIDENTS ON PAST "IN - THE - WET" CONSTRUCTION	
DATE	DESIGNED BY
	ECC
	DRAWING NO.
	3 OF 3

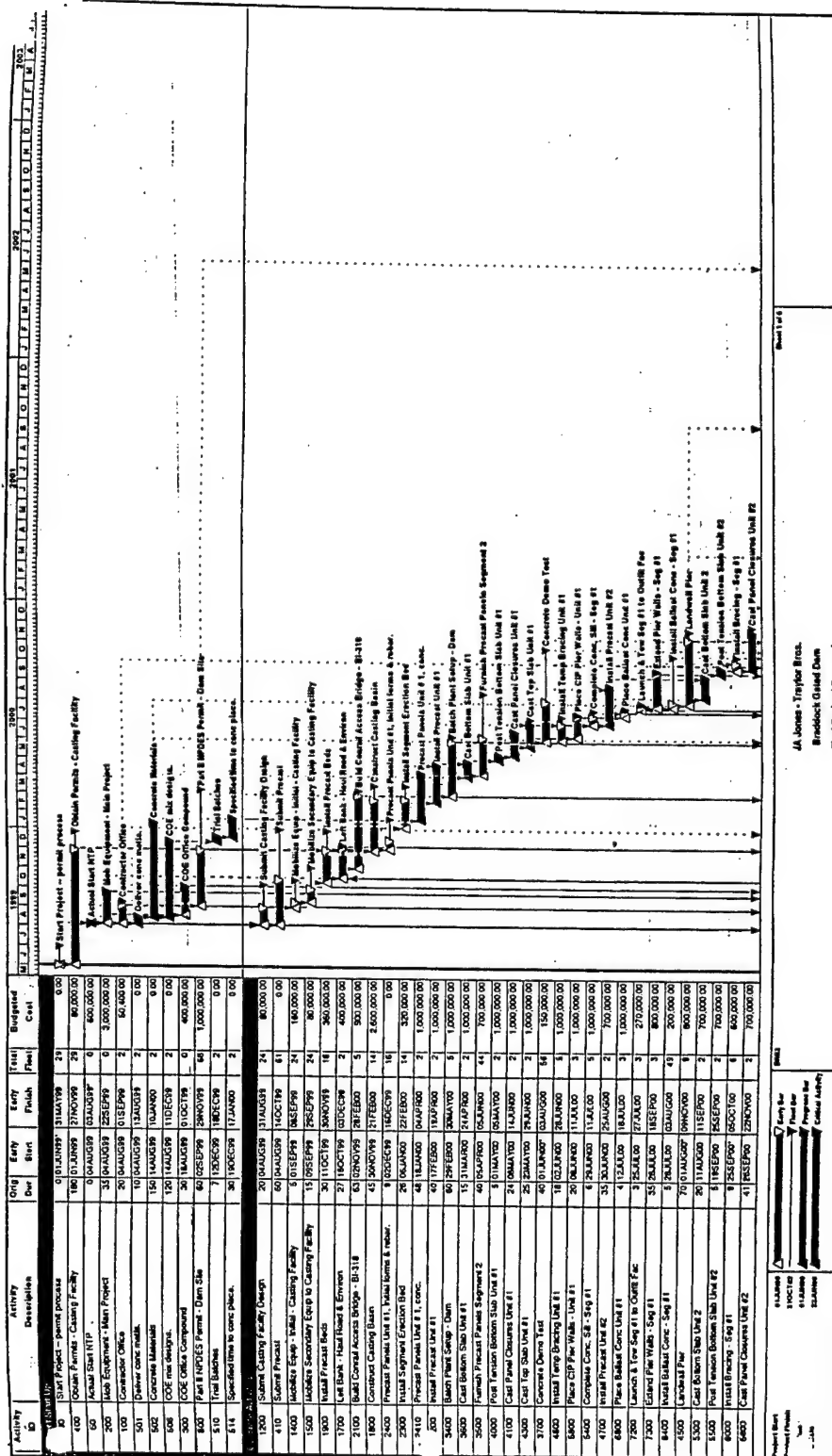
EVENT	STAGE	RESPONSIBILITY AND CAUSE	CONSEQUENCES	MITIGATION OR REPAIRS CARRIED OUT	PREVENTION IN FUTURE
Wandoo B - Partial damage to steel skirts	Transportation	Contractor. Impact on sea bottom during towing.	Delay in delivery of several weeks.	Divers removed damaged skirts and installed new skirts	Better definition of towing route to provide adequate water depth
Beryl A - Flooding of Utility Shaft	In-Service	Contractor. Failure to seal by grouting all of the underbase grouting injection hoses	Shut down of operations for several months. Loss of revenue.	Flow shut off by divers and aft dewatered. Damaged equipment replaced	Improved QA/QC procedures
Brent B - Damage to concrete surface due to dropped object	In-Service	Operator. Ten ton pipe dropped from crane on submerged concrete surface	Leakage of seawater into the structure and lengthy production shutdown. Loss of revenue.	Divers installed a strong steel plate over the damaged area and then a reinforced concrete cap was placed on that	Dropped object protection provided by lightweight concrete on submerged horizontal surfaces
Hibernia - Damage to concrete cover during slipforming operation	Fabrication	Contractor. Failure to properly clean formwork before commencing slipforming operation	Exposure of reinforcing steel to seawater environment. \$40 million repair cost.	Damaged concrete removed and special repair material applied using low-pressure spray up techniques	Improved QA/QC procedures
Generic for North Sea Structures - Damage to concrete due to ship impact	In-Service	Ship operator. Usually by out-of-control vessels	Typically limited to score marks up to 1-1/2 in. in depth. Occasional major damage.	Significant damaged to the concrete at the water line is repaired by re-forming and casting a new reinforced concrete surface	No solution to impact has been determined
Frigg CDP1 - Cracking of foundation	In-Service	Designer. Did not account for excessive differential settlements	Large cracks in cantilevered sections of the foundation have led to reinforcing bar corrosion	None	Improved geotechnical surveys. Use improved analysis techniques and provide adequate detailing of reinforcing.
Statford A and Statford C - Damage to concrete by hydro-carbon fire	In-Service	Operator. Leakage of production equipment resulting in intense fire	Spalling of concrete adjacent to fire. Shut down of production while reanalysis of structural integrity was performed	Damaged concrete and rebar removed and replaced	Improved inspection and maintenance of operating equipment
West Tuna and Bream B - Constructability	Fabrication	Designer and Contractor	Detailing and assembly of reinforcing bars did	Use of special reinforcing bars for shear reinforcement improved constructability	Better communication between the designer and the constructor.



problems				not allow proper placement of the concrete. 6 month construction delay.		
South Arne - Concrete production problems	Fabrication	Contractor. Use of a problematic LWA.	Concrete that was difficult to mix and place	None	Proper materials evaluation and mixture development prior to the start of construction	
Generic for Gulf Oil of Mexico Concrete Platforms - Severe corrosion of reinforcing steel on horizontal surfaces	In-Service	Designer and Contractor. Poor quality concrete and inadequate concrete cover.	Spalling of concrete surface due to rebar corrosion. Loss of bars.	Removal of contaminated concrete and deteriorated bars. Replaced with new rebar and concrete or polymer concrete	Use of concrete designed for marine applications and specifying adequate concrete cover.	

# **Appendix D Contractor's Final Revised Proposal; Construction Schedule—Braddock Gated Dam**

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Activity ID	Activity Description	Orig Dur	Early Start	Early Finish	Total Float	Budgeted Cost
7000	Furnish Tail Race Panels	32	02/01/00	02/29/00	137	750,000.00
7001	Transport Seg #1 to Dam Site	2	02/01/00	02/03/00	0	50,000.00
7002	Set Down Seg #1	2	02/01/00	02/03/00	0	200,000.00
7003	Cast Top Slabs & pier walls - Seg #2	40	02/01/00	03/10/00	2	1,400,000.00
7004	Under Base Grout Seg #1	5	02/01/00	02/06/00	0	461,500.00
7005	Cure U-Base Grout Seg #1	7	02/01/00	02/08/00	0	112,000.00
7006	Form Wall	15	02/01/00	02/16/00	58	1,893,000.00
7007	Form Wall	10	02/01/00	02/11/00	58	200,000.00
7008	Form Wall	10	02/01/00	02/11/00	161	150,000.00
7009	Form Wall	20	02/01/00	02/21/00	2	700,000.00
7010	Form Wall	45	02/01/00	03/10/00	58	538,875.00
7011	Form Wall	12	02/01/00	02/13/00	132	1,500,000.00
7012	Form Wall	60	02/01/00	03/23/00	211	0.00
7013	Form Wall	45	02/01/00	03/10/00	68	523,928.00
7014	Form Wall	10	02/01/00	02/11/00	132	1,000,500.00
7015	Form Wall	10	02/01/00	02/11/00	2	700,000.00
7016	Form Wall	40	02/01/00	03/10/00	132	46,500.00
7017	Form Wall	45	02/01/00	03/10/00	68	344,065.00
7018	Form Wall	5	02/01/00	02/06/00	2	700,000.00
7019	Form Wall	6	02/01/00	02/07/00	61	175,000.00
7020	Form Wall	3	02/01/00	02/04/00	1	50,000.00
7021	Form Wall	110	02/01/00	04/10/00	276	3,300,000.00
7022	Form Wall	25	02/01/00	02/26/00	1	700,000.00
7023	Form Wall	30	02/01/00	03/01/00	58	588,437.00
7024	Form Wall	30	02/01/00	03/01/00	68	361,964.00
7025	Form Wall	70	02/01/00	03/23/00	9	300,000.00
7026	Form Wall	15	02/01/00	02/16/00	1	350,000.00
7027	Form Wall	20	02/01/00	02/21/00	58	441,938.00
7028	Form Wall	5	02/01/00	02/06/00	68	84,190.00
7029	Form Wall	10	02/01/00	02/11/00	137	0.00
7030	Form Wall	2	02/01/00	02/03/00	0	50,000.00
7031	Form Wall	20	02/01/00	02/21/00	68	434,464.00
7032	Form Wall	5	02/01/00	02/06/00	79	100,378.00
7033	Form Wall	2	02/01/00	02/03/00	0	150,000.00
7034	Form Wall	1	02/01/00	02/02/00	0	0.00
7035	Form Wall	5	02/01/00	02/06/00	0	402,500.00
7036	Form Wall	10	02/01/00	02/11/00	129	0.00
7037	Form Wall	7	02/01/00	02/08/00	1	0.00
7038	Form Wall	10	02/01/00	02/11/00	68	50,000.00
7039	Form Wall	10	02/01/00	02/11/00	0	1,245,000.00
7040	Form Wall	20	02/01/00	02/21/00	78	50,000.00
7041	Form Wall	45	02/01/00	03/10/00	102	0.00
7042	Form Wall	10	02/01/00	02/11/00	0	548,065.00
7043	Form Wall	45	02/01/00	03/10/00	117	1,050,000.00
7044	Form Wall	6	02/01/00	02/07/00	28	332,335.00
7045	Form Wall	30	02/01/00	03/01/00	117	581,800.00
7046	Form Wall	45	02/01/00	03/10/00	71	538,609.00
7047	Form Wall	16	02/01/00	02/17/00	20	251,545.00
7048	Form Wall	26	02/01/00	03/01/00	44	251,545.00
7049	Form Wall	15	02/01/00	02/16/00	55	96,221.00

**THE UNIVERSITY OF CHICAGO**

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Activity ID	Activity Description	Orig Dur	Early Start	Early Finish	Total Float	Budgeted Cost	2009											
							J	F	M	A	M	J	J	A	S	O	N	D
20700	Stage 45 - Dredge	15	13SEP02	30SEP02	19	721,000.00												
400	Stage 44 - Dredge (Phase 2)	8	18SEP02	07OCT02	0	424,000.00												
50000	Install Rip-Rap - Left Bank	11	06OCT02	22OCT02	0	1,251,700.00												
50000	Install Piers Warning Signs	6	23OCT02	30OCT02	0	74,000.00												
20800	Install & Develop Island Walls	20	07AUG02	06AUG02	5	0.00												
19900	Close & LF of Existing Dam - Lower Pool	5	14AUG02	20AUG02	0	300,000.00												
19900	Remove Remaining Old Dam - Dike & Shod	15	22AUG02	07AUG02	21	300,000.00												
20300	Remove Old Dam - Chain Material	14	09AUG02	23AUG02	21	300,000.00												
20300	Remove Old Dam - Dispose Material	15	23AUG02	10SEP02	21	300,000.00												
20900	Final Cleanup - Punch List	15	30SEP02	18OCT02	8	0.00												
30100	Restore Seed RIDC	5	01OCT02	07OCT02	16	257,000.00												
39999	End Project	1	31OCT02	31OCT02	0	0.00												



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14. ABSTRACT  This report summarizes methods and procedures to assist engineers in performing risk assessments for innovative navigation projects. Detailed descriptions of the methodologies that can be used in risk assessments are highlighted. An example float-in dam is used to document the risk assessment process. This process includes hazard identification, risk evaluation and analysis, and eventual risk mitigation.  A database of historical marine construction problems and failures is also included for similar float-in construction projects. Conclusions and recommendations are made to further assist future risk assessment projects for innovative structures and to help direct additional research in this area.																	
15. SUBJECT TERMS <table border="0"> <tr> <td>Construction failures</td> <td>Hazard identification</td> <td>Risk</td> <td>Uncertainties</td> </tr> <tr> <td>Dams</td> <td>Innovative</td> <td>Risk assessment</td> <td></td> </tr> <tr> <td>Float-in</td> <td>Marine construction</td> <td>Risk mitigation</td> <td></td> </tr> </table>						Construction failures	Hazard identification	Risk	Uncertainties	Dams	Innovative	Risk assessment		Float-in	Marine construction	Risk mitigation	
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16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES  92	19a. NAME OF RESPONSIBLE PERSON												
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